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Cross sections at the LHC

J. Huston
Michigan State University
and IPPP-Durham

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Pavel's response to my giving his talk yesterday

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Some references

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Hard interactions of quarks and gluons: a primer for LHC physics

CHS

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Abstract

In this paper, we will develop the perturbative framework for the calculation of hard-scattering processes. We will undertake to provide both a reasonably rigorous development of the formalism of hard-scattering of quarks and gluons as well as an intuitive understanding of the physics behind the scattering. We will emphasize the role of logarithmic corrections as well as power counting in α_S in order to understand the behaviour of hard-scattering processes. We will include 'rules of thumb' as well as 'official recommendations', and where possible will seek to dispel some myths. We will also discuss the impact of soft processes on the measurements of hard-scattering processes. Experiences that have been gained at the Fermilab Tevatron will be recounted and, where appropriate, extrapolated to the LHC.

(Some figures in this article are in colour only in the electronic version)

goal is to provide a reasonably global picture of LHC calculations (with rules of thumb)

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Progress in Particle and Nuclear Physics 60 (2008) 484–551

Progress in Particle and Nuclear Physics

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Review

Jets in hadron–hadron collisions

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arXiv:07122447 Dec 14, 2007

Abstract

In this article, we review some of the complexities of jet algorithms and of the resultant comparisons of data to theory. We review the extensive experience with jet measurements at the Tevatron, the extrapolation of this acquired wisdom to the LHC and the differences between the Tevatron and LHC environments. We also describe a framework (SpartyJet) for the convenient comparison of results using different jet algorithms.

Keywords: Jet; Jet algorithm; LHC; Tevatron; Perturbative QCD; SpartyJet

Contents

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More references

- If you’re rushed for time


explain it in 60 seconds

Jets are sprays of particles that fly out from certain high-energy collisions—for instance, from violent collisions of protons and antiprotons at Fermilab's Tevatron accelerator, or in the similar proton-proton collisions that will take place at CERN's Large Hadron Collider.

These collisions create very energetic quarks and gluons; as they travel away from the collision point, they emit more gluons, which can split into even more gluons. This results in a relatively narrow cascade, or jet, of particles.

In the last stage of jet creation, quarks and gluons combine to form particles such as protons, pions, and kaons. By measuring these end products, physicists can determine the properties of a jet, and thus the details of the collision that produced it. Scientists expect to see jets in the signatures of almost every interesting collision at the Large Hadron Collider.

The most violent collisions will produce jets with the highest momentum, and these can be used to probe the smallest distances within the colliding protons, less than one-billionth of a billionth of a meter. Physicists hope they can use these most energetic jets to look inside the quarks that make up protons.

Joey Huston, Michigan State University

“When you're a jet,
you're a jet all the way,
from your first gluon split
to your last K decay...”

Symmetry
A joint Fermilab/SLAC publication
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MS 206
Batavia Illinois 60510
USA

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Donald Rumsfeld

- I will not be referring to Donald Rumsfeld in this talk…as I have in some previous talks

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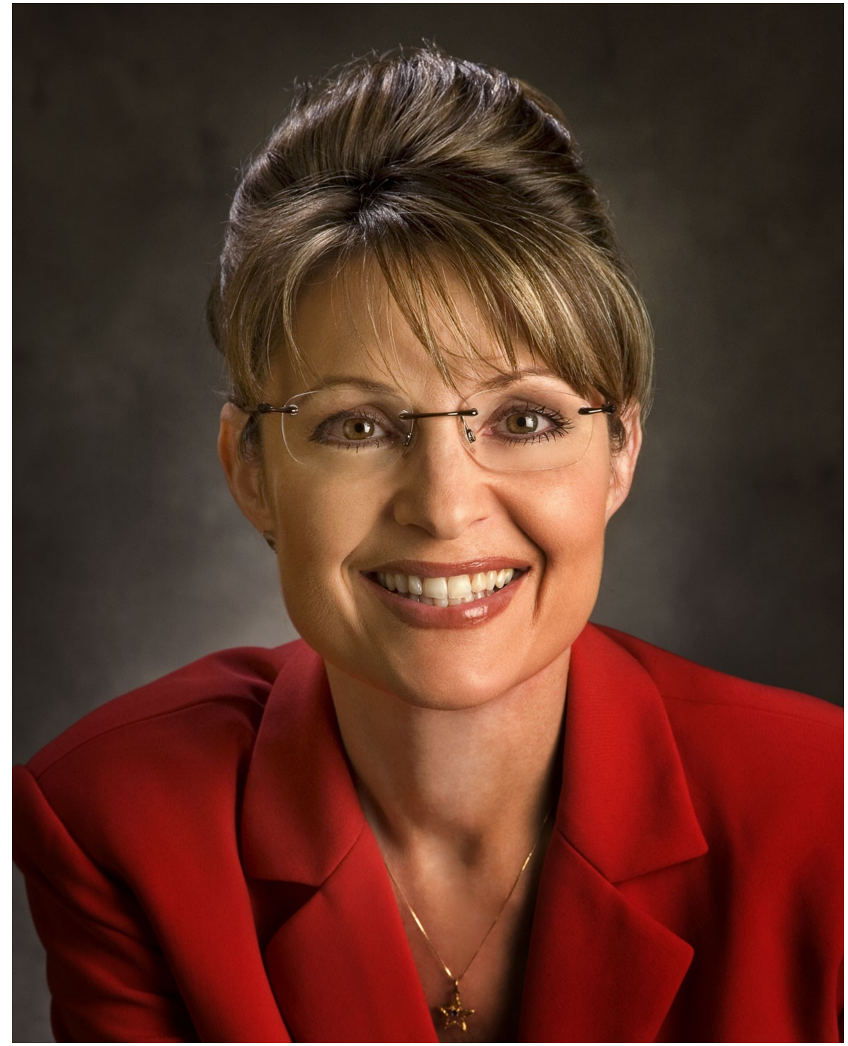
- Besides, who needs to, now that we have Sarah Palin…at least until 2012



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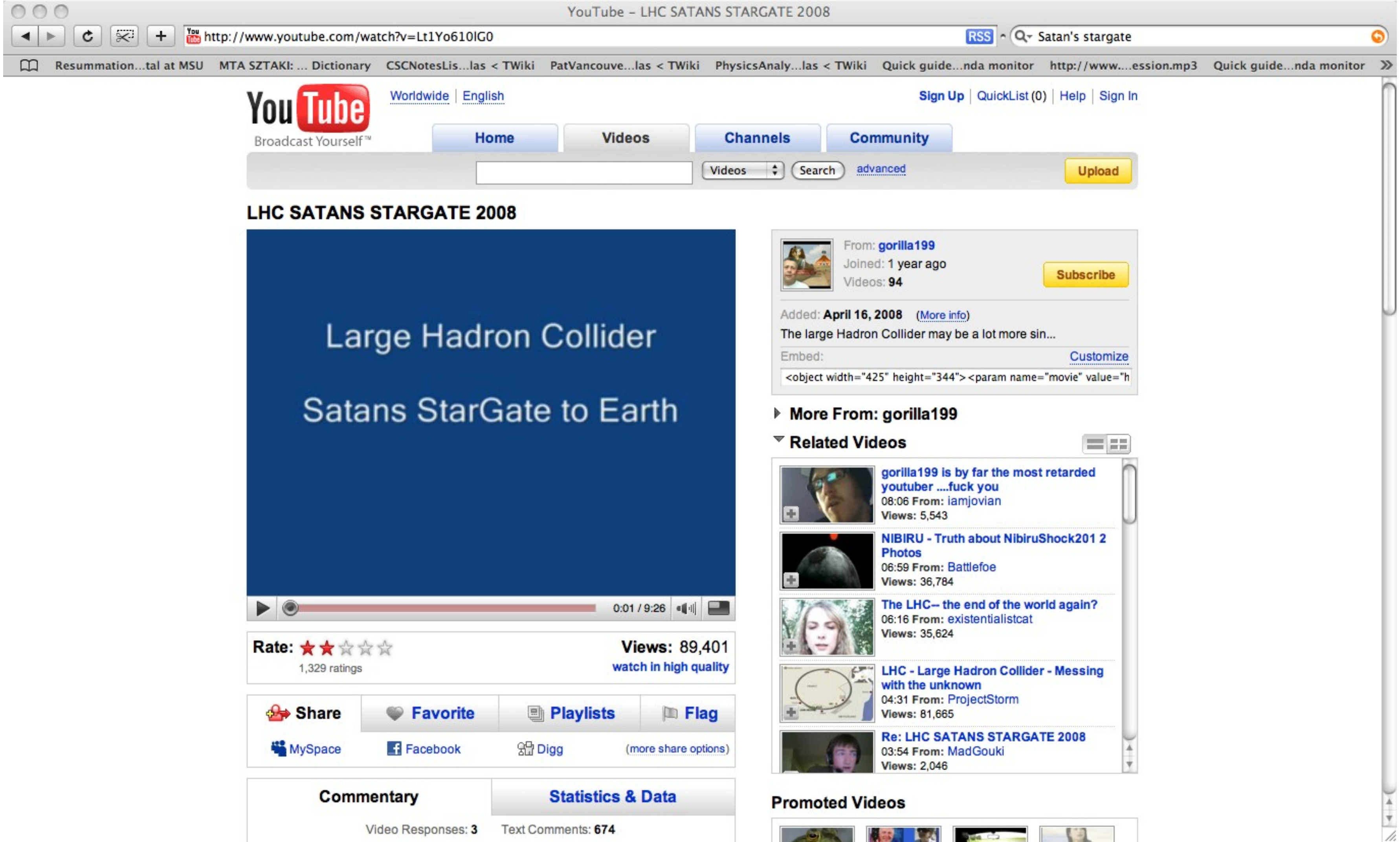
Cross sections at the LHC

- …or as some like to call it



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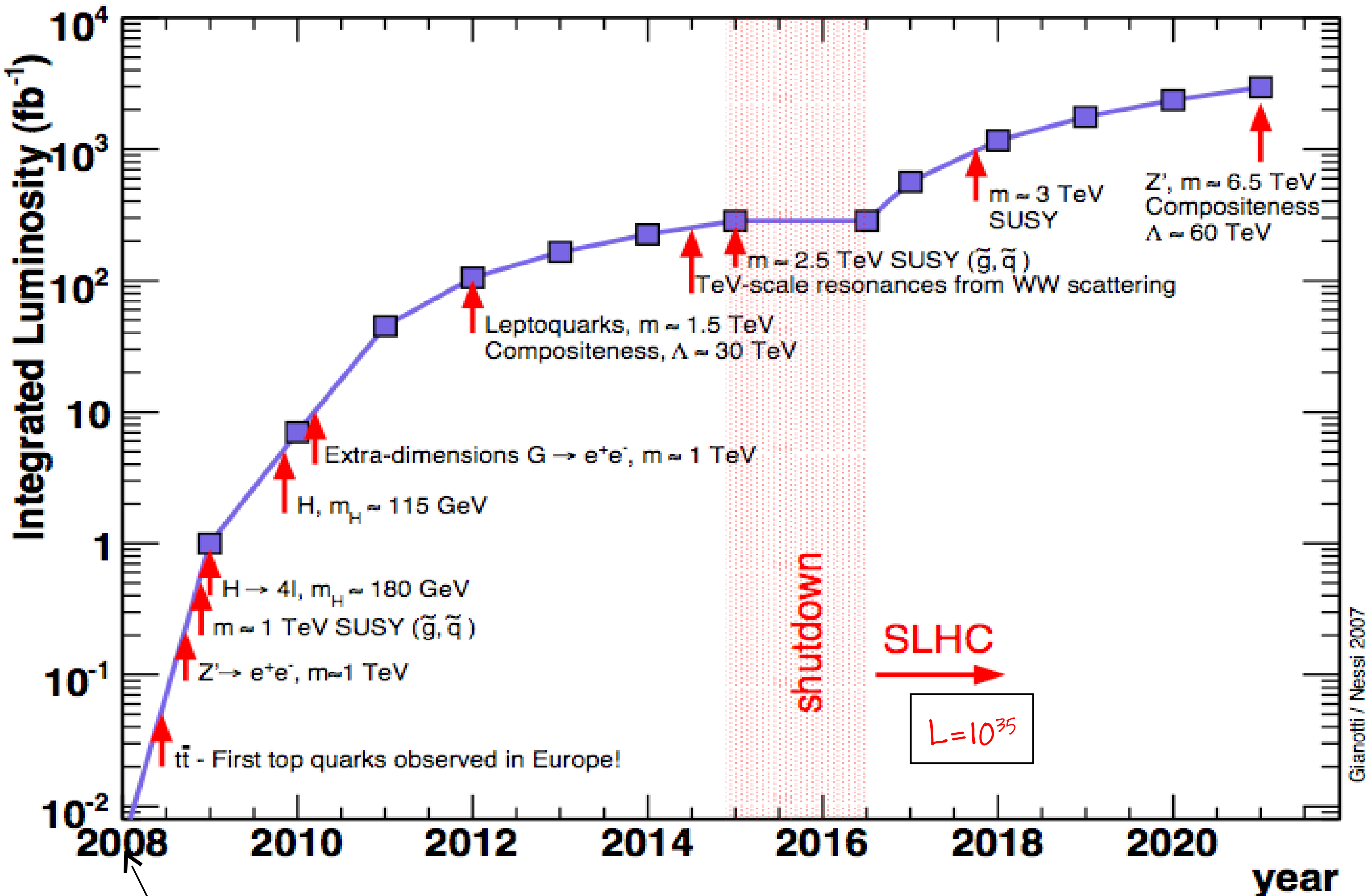
We'll look back on early trouble in 15 years and laugh

LHC vs time: a wild guess …



you are here

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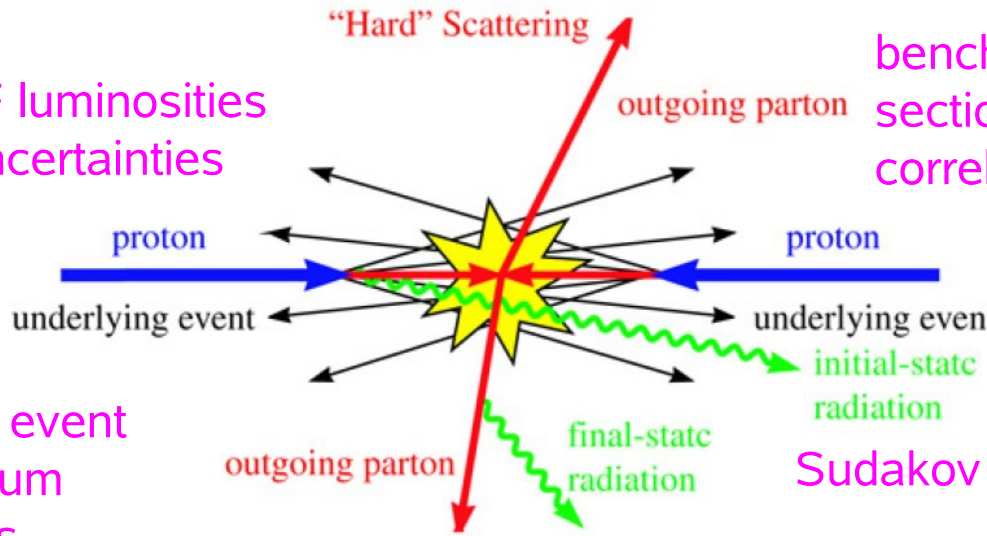
Understanding cross sections at the LHC

…but before we can laugh

LO, NLO and NNLO calculations
K-factors

PDF's, PDF luminosities
and PDF uncertainties

benchmark cross
sections and pdf
correlations



underlying event
and minimum
bias events

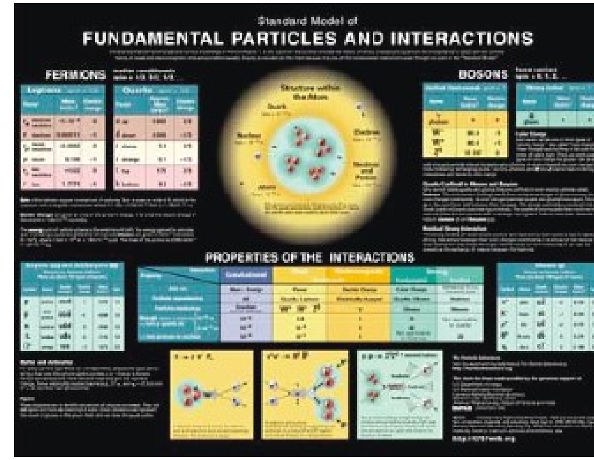
Sudakov form factors

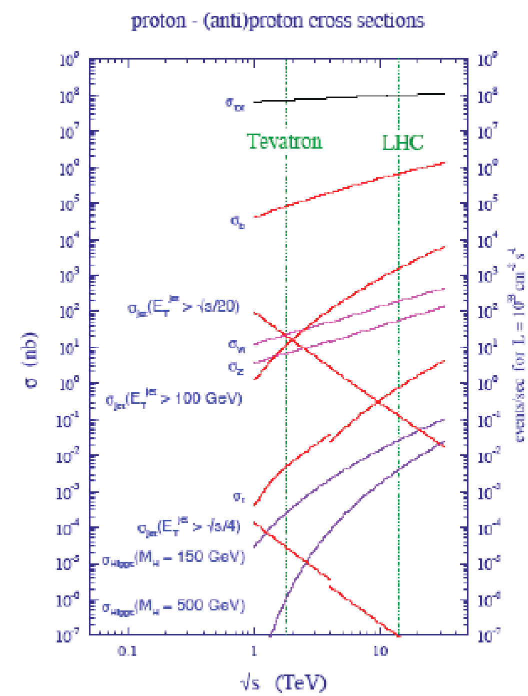
jet algorithms and jet reconstruction

I'll try to touch on these topics in this lecture.

Understanding cross sections at the LHC

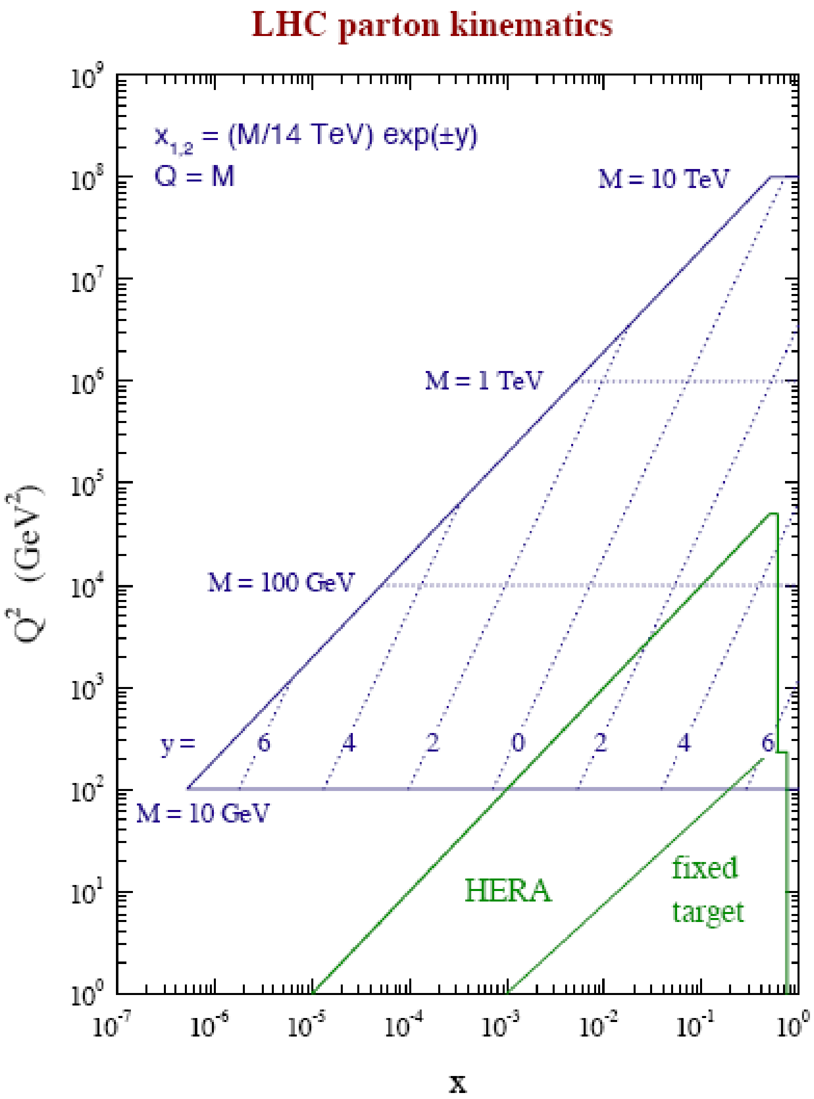
- We’re all looking for BSM physics at the LHC
- Before we publish BSM discoveries from the early running of the LHC, we want to make sure that we measure/understand SM cross sections
    - detector and reconstruction algorithms operating properly
    - SM physics understood properly
    - SM backgrounds to BSM physics correctly taken into account
    - and in particular (for these lectures at least) that pdf’s and pdf uncertainties are understood properly





Cross sections at the LHC

- Experience at the Tevatron is very useful, but scattering at the LHC is not necessarily just “rescaled” scattering at the Tevatron
- Small typical momentum fractions x in many key searches
  - dominance of gluon and sea quark scattering
  - large phase space for gluon emission and thus for production of extra jets
  - intensive QCD backgrounds
  - or to summarize,…lots of Standard Model to wade through to find the BSM pony



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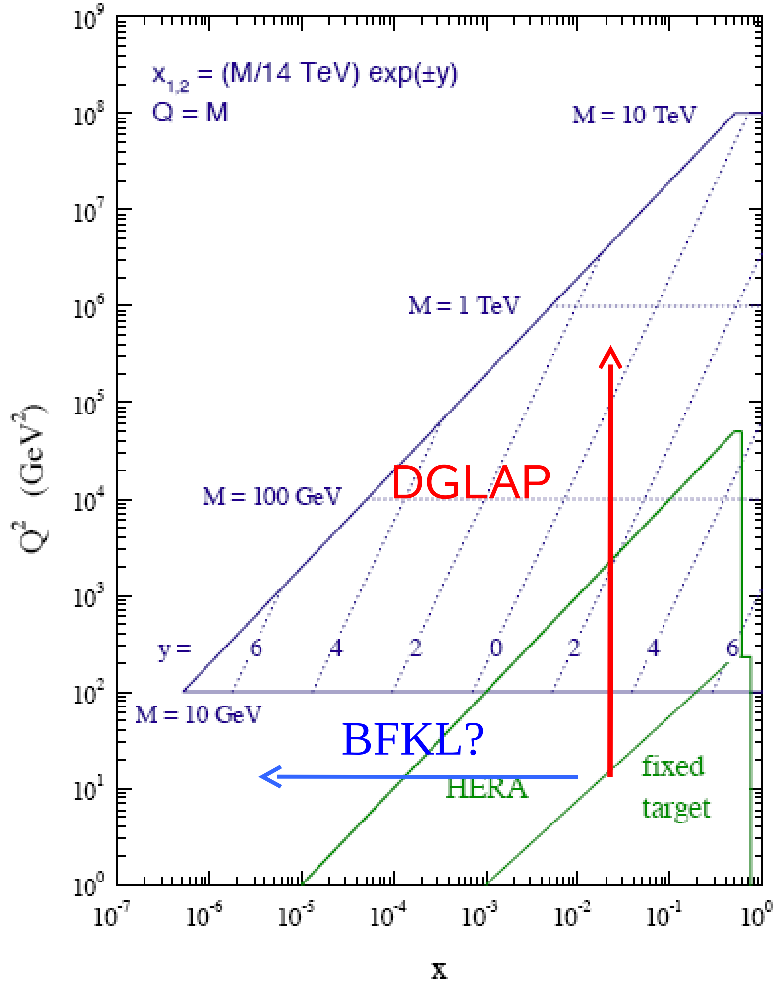
Cross sections at the LHC

- Note that the data from HERA and fixed target cover only part of kinematic range accessible at the LHC
- We will access pdf's down to 1E-6 (crucial for the underlying event) and Q^2 up to 100 TeV^2
- We can use the DGLAP equations to evolve to the relevant x and Q^2 range, but…
  - we're somewhat blind in extrapolating to lower x values than present in the HERA data, so uncertainty may be larger than currently estimated
  - we're assuming that DGLAP is all there is; at low x BFKL type of logarithms may become important

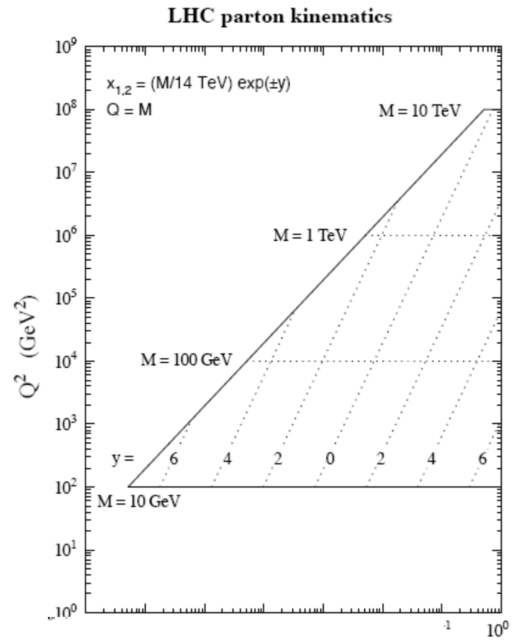
$$\frac{d\sigma}{dM^2 dy} = \frac{\hat{\sigma}_0}{Ns}\left[\sum_k Q_k^2 (q_k(x_1, M^2)\bar{q}_k(x_2, M^2) + [1 \leftrightarrow 2])\right]$$

LHC parton kinematics



Parton kinematics at the LHC

- To serve as a handy "look-up" table, it's useful to define a parton-parton luminosity (mentioned earlier)
- Equation 3 can be used to estimate the production rate for a hard scattering at the LHC as the product of a differential parton luminosity and a scaled hard scatter matrix element



$$\frac{dL_{ij}}{d\hat{s}\,dy} = \frac{1}{s}\,\frac{1}{1+\delta_{ij}}\left[f_i(x_1,\mu)f_j(x_2,\mu) + (1 \leftrightarrow 2)\right]. \qquad (1)$$

The prefactor with the Kronecker delta avoids double-counting in case the partons are identical. The generic parton-model formula

this is from the CHS review paper

$$\sigma = \sum_{i,j}\int_0^1 dx_1\,dx_2\,f_i(x_1,\mu)\,f_j(x_2,\mu)\,\hat{\sigma}_{ij} \qquad (2)$$

can then be written as

$$\sigma = \sum_{i,j}\int\left(\frac{d\hat{s}}{\hat{s}}\,dy\right)\left(\frac{dL_{ij}}{d\hat{s}\,dy}\right)(\hat{s}\,\hat{\sigma}_{ij}) \ . \qquad (3)$$

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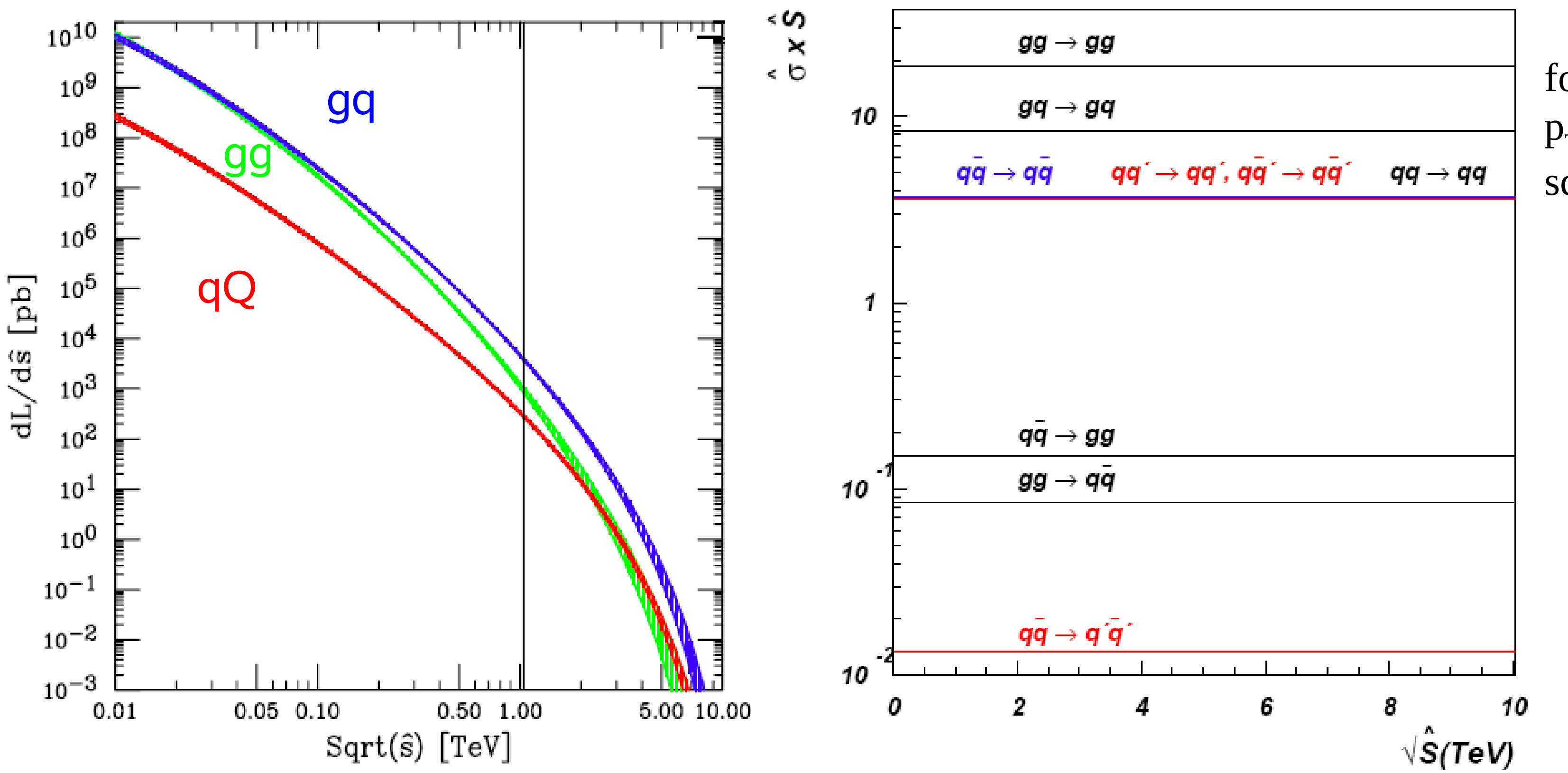
Cross section estimates

$$\sigma = \frac{\Delta\hat{s}}{\hat{s}}\left(\frac{dL_{ij}}{d\hat{s}}\right)(\hat{s}\,\hat{\sigma}_{ij})$$

for the gluon pair production rate for $\hat{s}$=1 TeV and $\Delta\hat{s} = 0.01\hat{s}$,
we have $\frac{dL_{gg}}{d\hat{s}} \simeq 10^3$ pb and $\hat{s}\,\hat{\sigma}_{gg} \simeq 20$ leading to $\sigma \simeq 200$ pb



for p_T=0.1* sqrt(s-hat)

Fig. 2: Left: luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$. Right: parton level cross sections $[\hat{s}\hat{\sigma}_{ij}]$ for various processes

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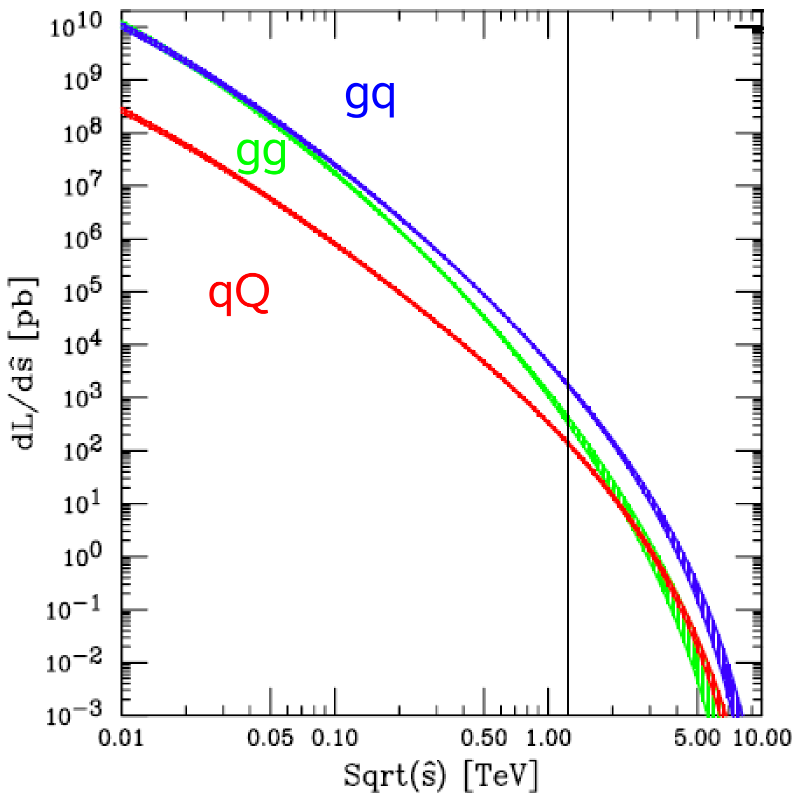
Heavy quark production

$$\sigma = \frac{\Delta\hat{s}}{\hat{s}}\left(\frac{dL_{ij}}{d\hat{s}}\right)(\hat{s}\,\hat{\sigma}_{ij})$$

threshold effects evident



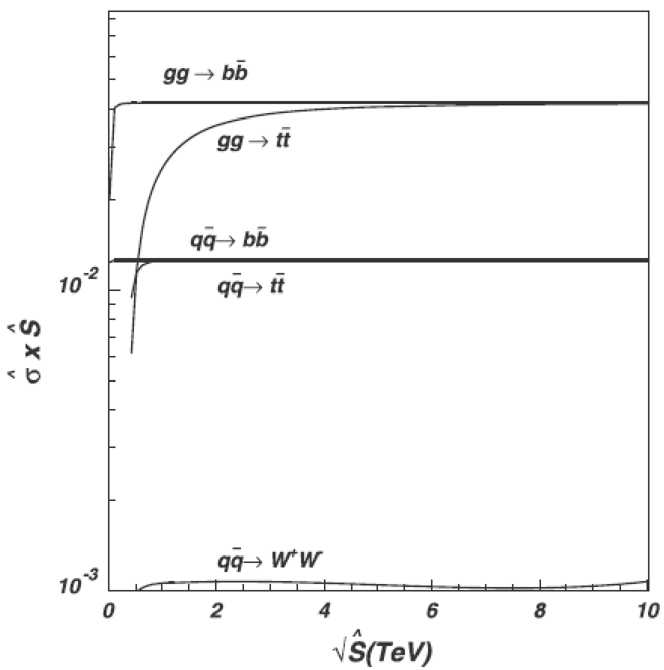


Figure 71. Parton level cross sections $(\hat{s}\hat{\sigma}_{ij})$ for various processes involving massive partons in the final state.

$\sqrt{S}$(TeV)

Fig. 2: Left: luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$. Right: parton level cross sections $[\hat{s}\hat{\sigma}_{ij}]$ for various processes

PDF luminosities as a function of y

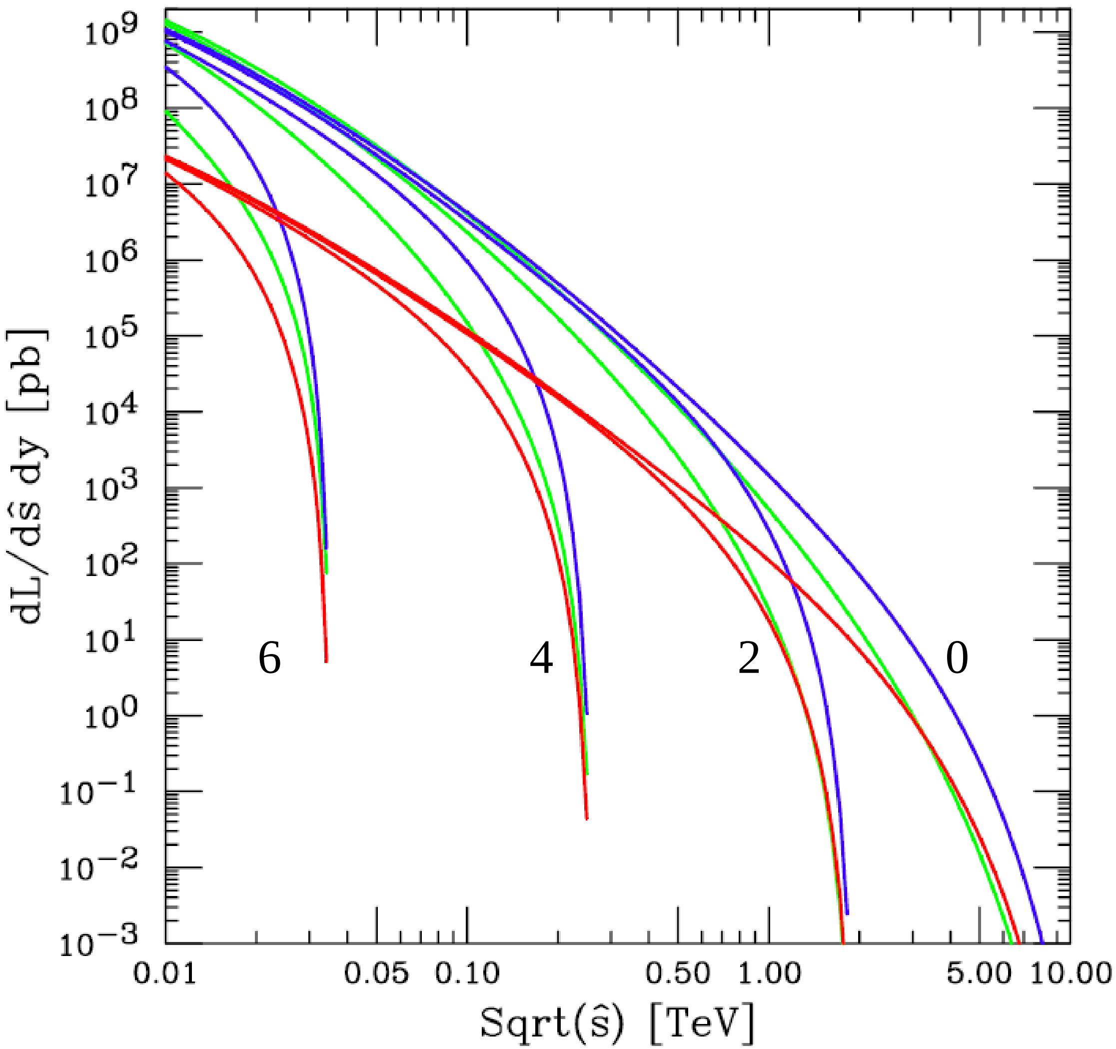
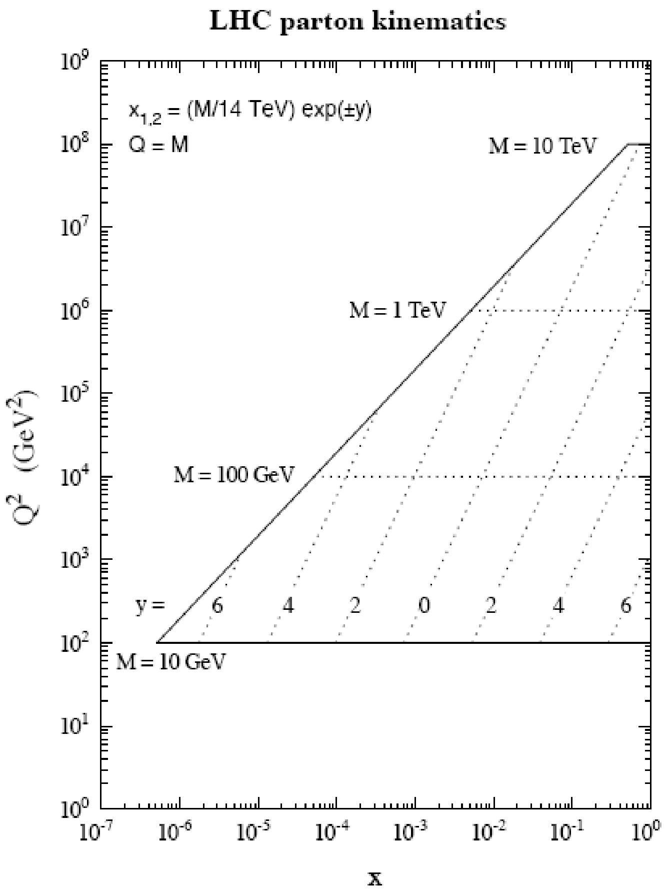


Fig. 3: dLuminosity/dy at $y = 0, 2, 4, 6$. Green=gg, Blue=$g(d + u + s + c + b) + g(\bar{d} + \bar{u} + \bar{s} + \bar{c} + \bar{b}) + (d + u + s + c + b)g + (\bar{d} + \bar{u} + \bar{s} + \bar{c} + \bar{b})g$, Red=$d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.



PDF uncertainties at the LHC

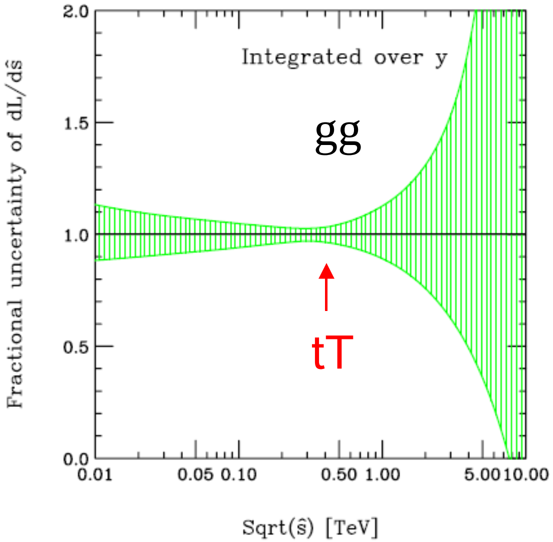


Fig. 4: Fractional uncertainty of gg luminosity integrated over y.

Note that for much of the SM/discovery range, the pdf luminosity uncertainty is small

Need similar level of precision in theory calculations

It will be a while, i.e. not in the first fb^{-1}, before the LHC data starts to constrain pdf's

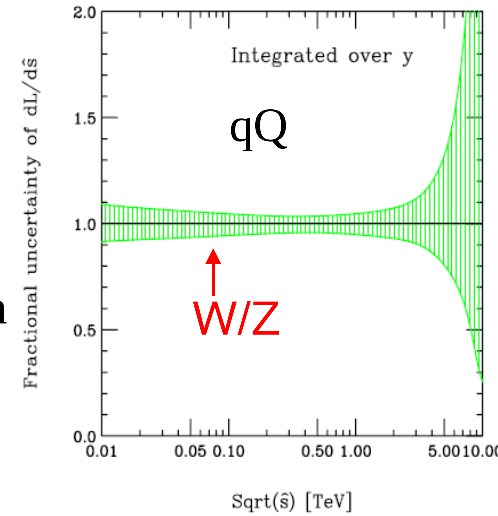


Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.

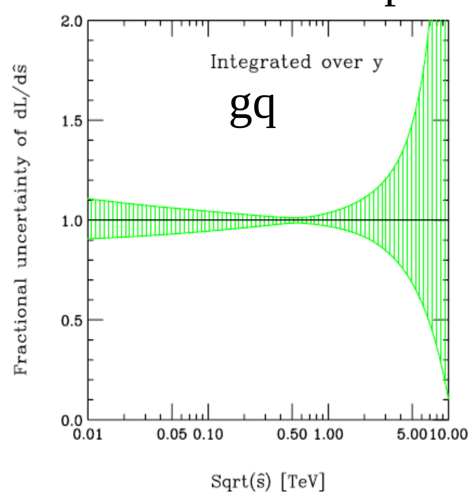


Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d+u+s+c+b) + g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b}) + (d+u+s+c+b)g + (\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$,

NBIII: tT uncertainty is of the same order as W/Z production

NB I: the errors are determined using the Hessian method for a $\Delta\chi^2$ of 100 using only experimental uncertainties,i.e. no theory uncertainties

NB II: the pdf uncertainties for W/Z cross sections are not the smallest

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Ratios:LHC to Tevatron pdf luminosities

- Processes that depend on qQ initial states (e.g. chargino pair production) have small enchancements
- Most backgrounds have gg or gq initial states and thus large enhancement factors (500 for W + 4 jets for example, which is primarily gq) at the LHC
- W+4 jets is a background to tT production both at the Tevatron and at the LHC
- tT production at the Tevatron is largely through a qQ initial states and so qQ->tT has an enhancement factor at the LHC of ~10
- Luckily tT has a gg initial state as well as qQ so total enhancement at the LHC is a factor of 100
    - but increased W + jets background means that a higher jet cut is necessary at the LHC
    - known known: jet cuts have to be higher at LHC than at Tevatron

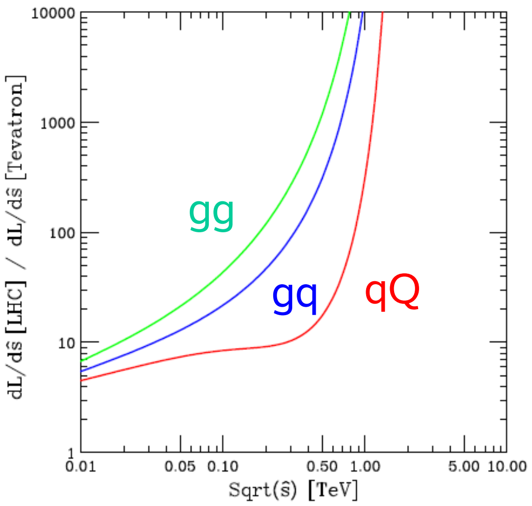

Figure 11. The ratio of parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y at the LHC and Tevatron. Green=gg (top), Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$ (middle), Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$ (bottom).

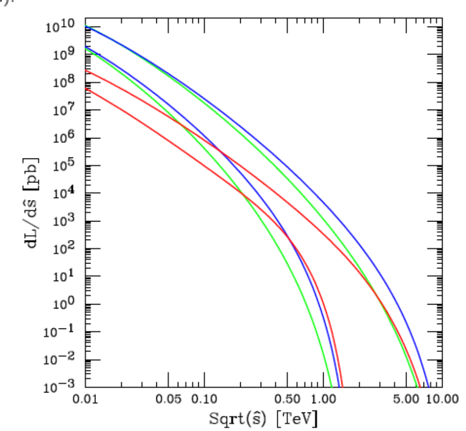

Figure 10. The parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$. The top family of curves are for the LHC and the bottom for the Tevatron.

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The LHC will be a very *jetty* place

- Total cross sections for tT and Higgs production saturated by tT (Higgs) + jet production for jet p_T values of order 10-20 GeV/c
- $\sigma_{\text{W+3 jets}} > \sigma_{\text{W+2 jets}}$

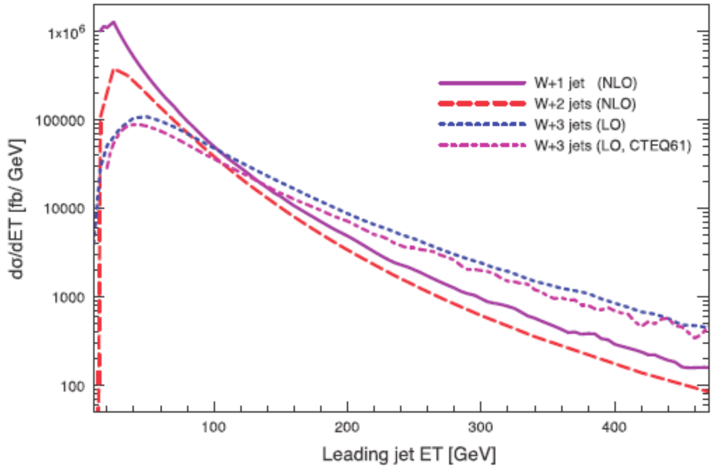

Figure 91. Predictions for the production of $W+ \geqslant 1, 2, 3$ jets at the LHC shown as a function of the transverse energy of the lead jet. A cut of 20 GeV has been placed on the other jets in the prediction.

- indication that can expect interesting events at LHC to be very *jetty* (especially from gg initial states)
- also can be understood from point-of-view of Sudakov form factors

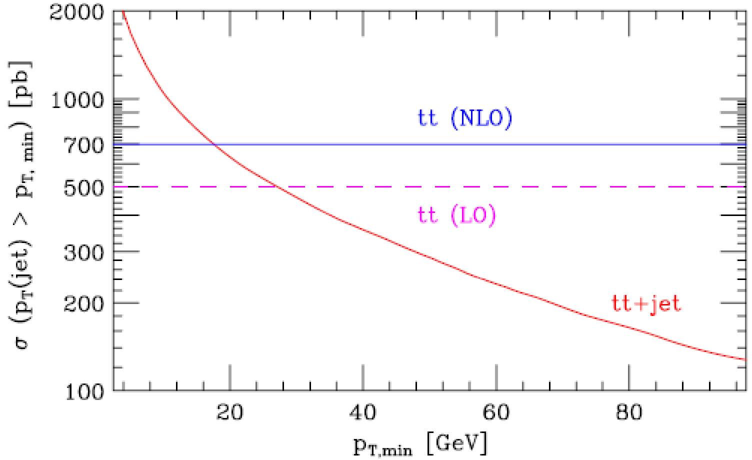

Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

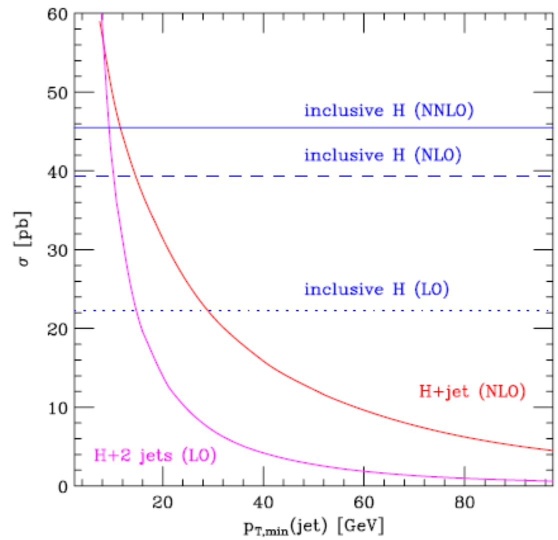

Figure 100. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

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Aside: Sudakov form factors

- Sudakov form factors form the basis for both resummation and parton showering
- We can write an expression for the Sudakov form factor of an initial state parton in the form below, where *t* is the hard scale, to is the cutoff scale and *P(z)* is the splitting function

$$\Delta(t) \equiv \exp\left[-\int_{t_0}^{t} \frac{dt'}{t'} \int \frac{dz}{z} \frac{\alpha_S}{2\pi} P(z) \frac{f(x/z,t)}{f(x,t)} \right]$$

- Similar form for the final state but without the pdf weighting
- Sudakov form factor resums all effects of soft and collinear gluon emission, but does not include non-singular regions that are due to large energy, wide angle gluon emission
- Gives the probability **not** to radiate a gluon greater than some energy

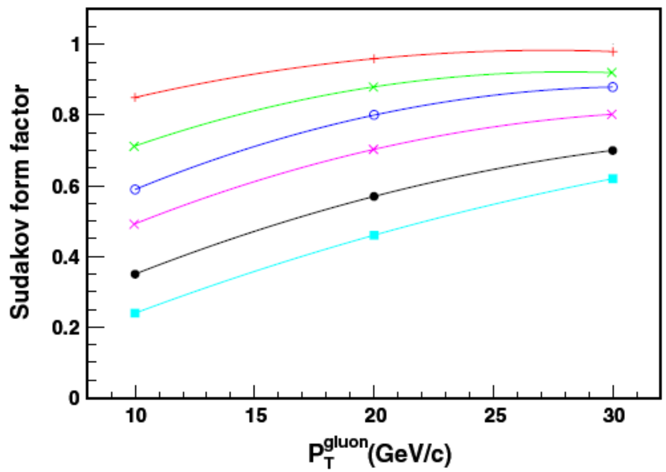

Figure 21. The Sudakov form factors for initial-state gluons at a hard scale of 100 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

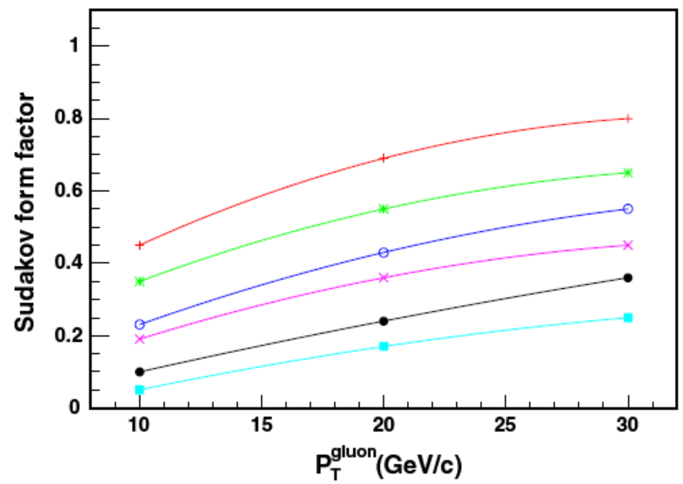

Figure 22. The Sudakov form factors for initial-state gluons at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

Aside: Sudakov form factors

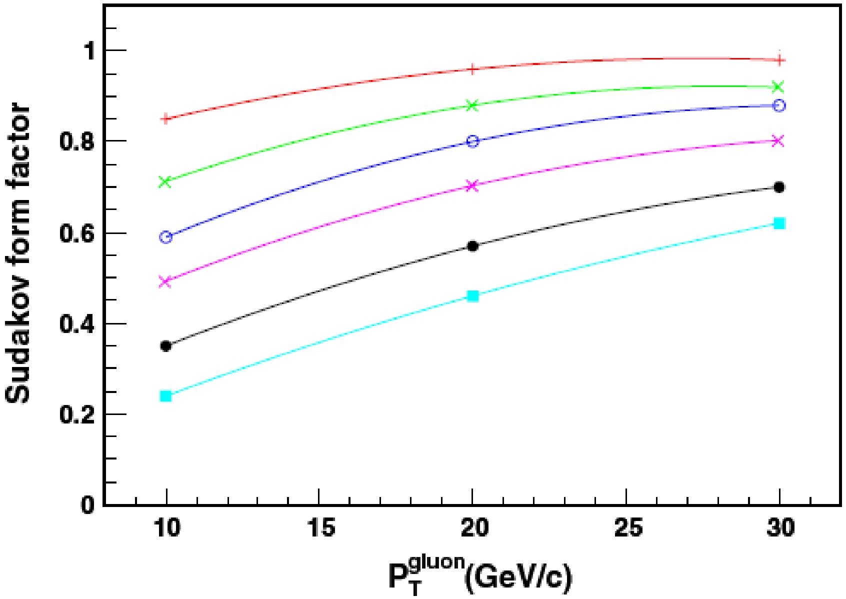

Figure 21. The Sudakov form factors for initial-state gluons at a hard scale of 100 GeV as a functio of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parto x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

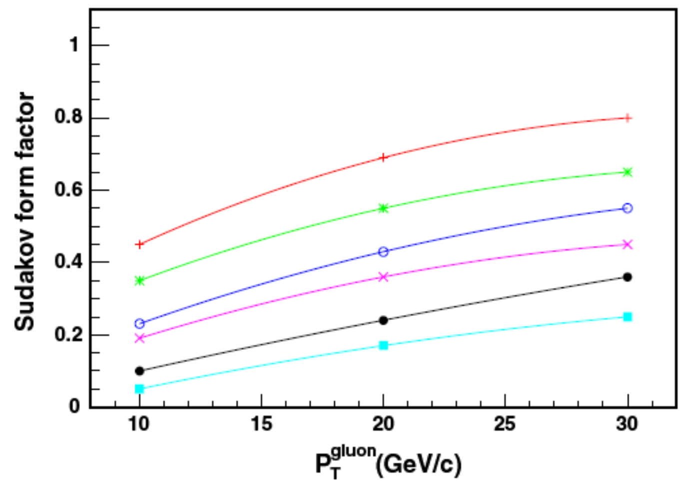

Figure 22. The Sudakov form factors for initial-state gluons at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

Sudakov form factors for tT

- tT production at the LHC dominated by gg at x values factor of 7 lower than Tevatron
- So dominant Sudakov form factor goes from
- to

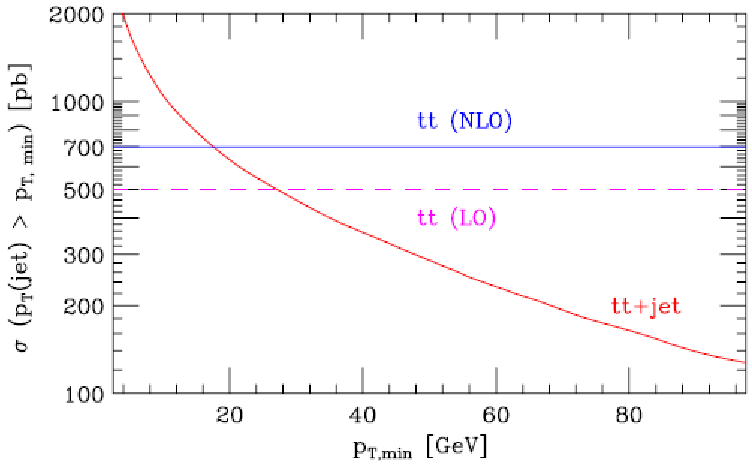

Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

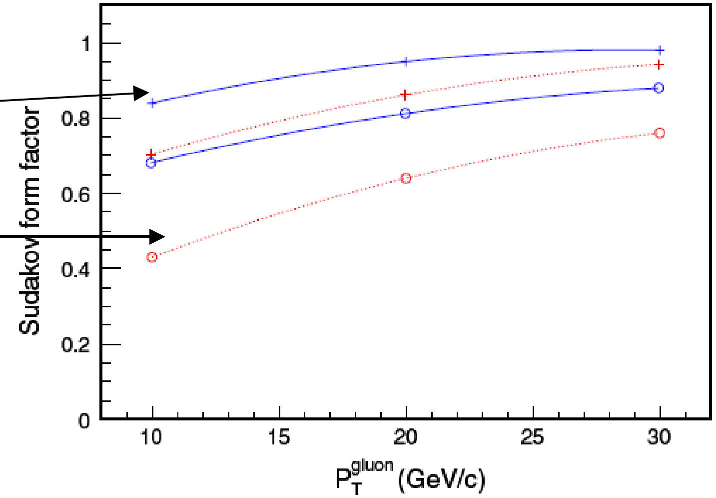

Figure 96. The Sudakov form factors for initial-state quarks and gluons at a hard scale of 200 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for quarks (blue-solid) and gluons (red-dashed) at parton x values of 0.3 (crosses) and 0.03 (open circles).

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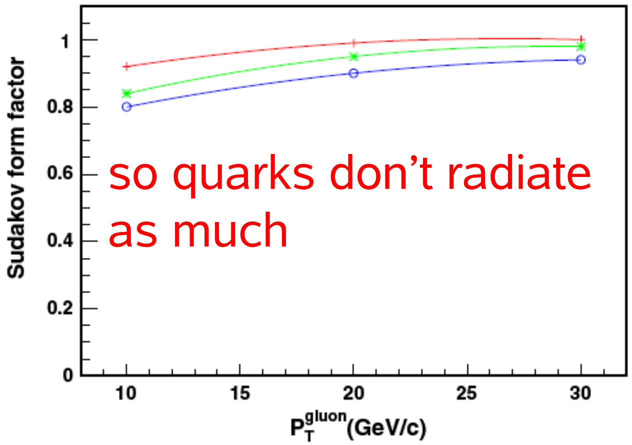
Sudakov form factors: quarks and gluons



so quarks don't radiate as much

Figure 23. The Sudakov form factors for initial-state quarks at a hard scale of 100 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1 and 0.03.

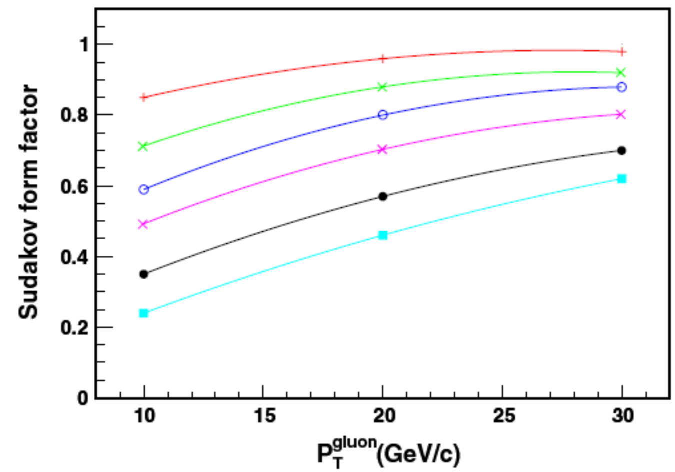


Figure 21. The Sudakov form factors for initial-state gluons at a hard scale of 100 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

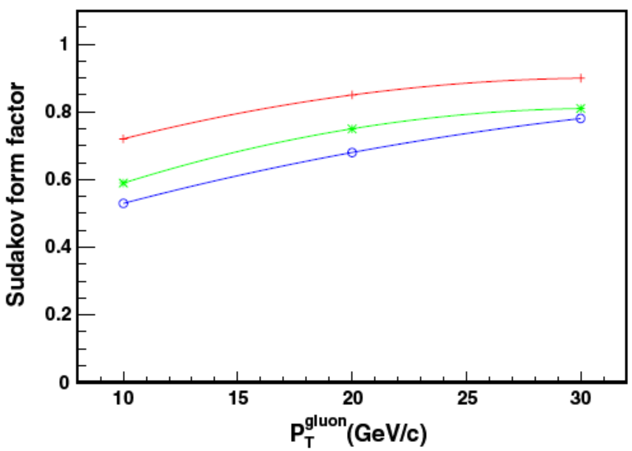


Figure 24. The Sudakov form factors for initial-state quarks at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1 and 0.03.

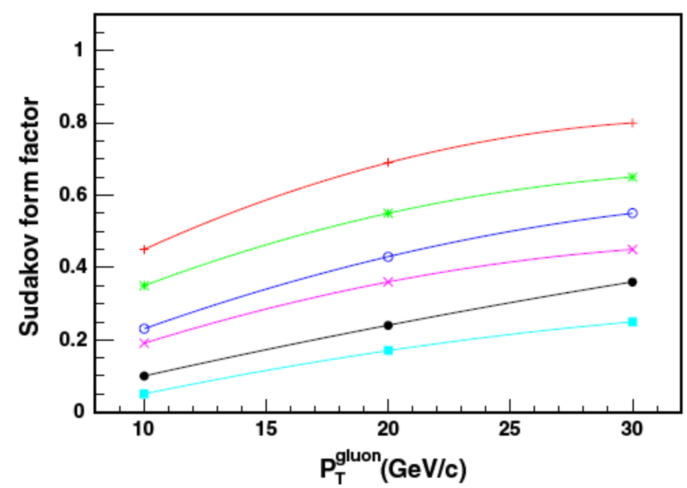
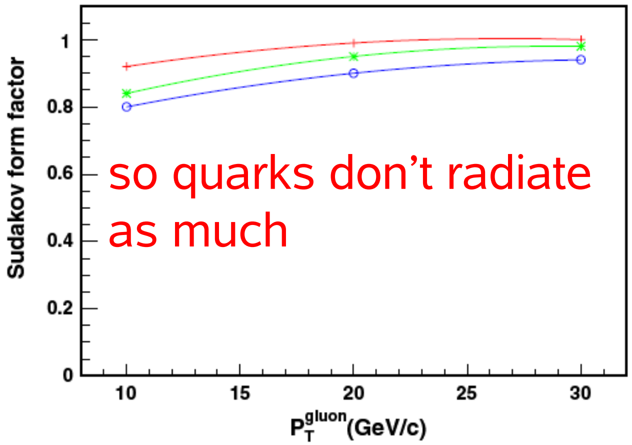


Figure 22. The Sudakov form factors for initial-state gluons at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

Sudakov form factors: quarks and gluons



so quarks don’t radiate as much

Figure 23. The Sudakov form factors for initial-state quarks at a hard scale of 100 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1 and 0.03.

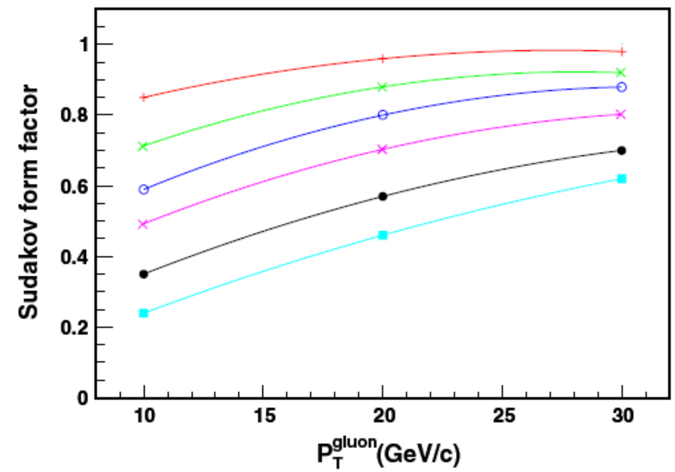
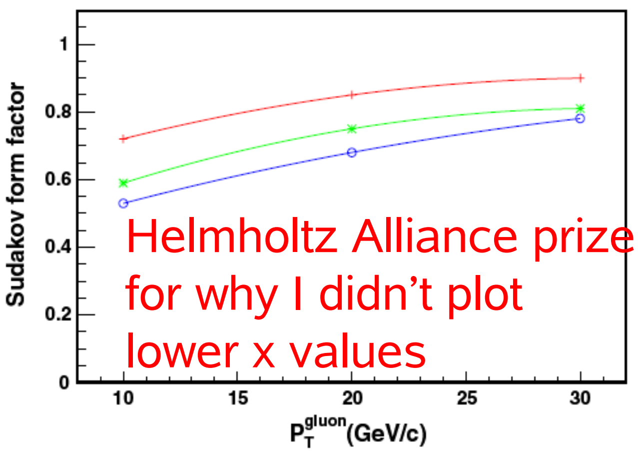


Figure 21. The Sudakov form factors for initial-state gluons at a hard scale of 100 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.



Helmholtz Alliance prize for why I didn’t plot lower x values

Figure 24. The Sudakov form factors for initial-state quarks at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1 and 0.03.

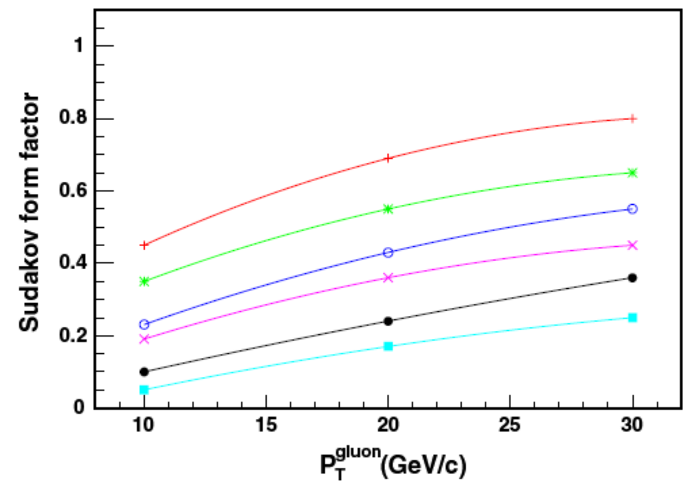


Figure 22. The Sudakov form factors for initial-state gluons at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

C T E Q

Helmholtz Prize

CTEQ

Benchmarks/cross section measurements at the LHC

C T E Q

Known unknown: underlying event at the LHC

- There’s a great deal of uncertainty regarding the level of underlying event at 14 TeV, but it’s clear that the UE is larger at the LHC than at the Tevatron
- Should be able to establish reasonably well with the first collisions in 2009 (at 10 TeV)
- We will need to take the effects of the underlying event into account when comparing LHC data to theory

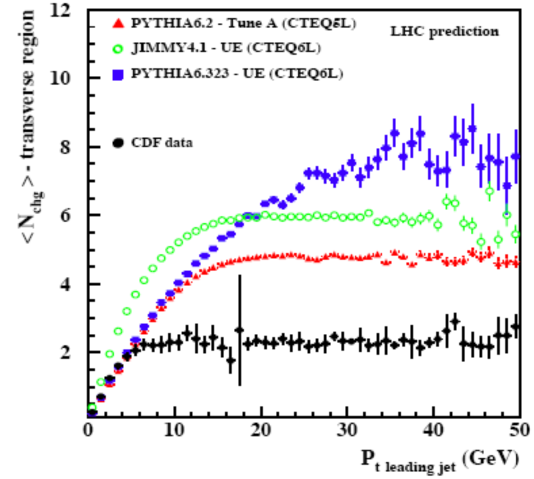
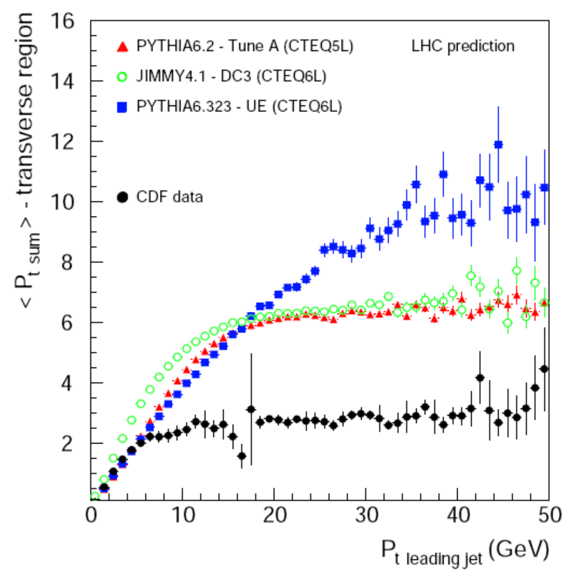


Figure 6: Pythia6.2 - Tune A, Jimmy4.1 - UE and Pythia6.323 - UE predictions for the average charged multiplicity in the underlying event for LHC pp collisions.



C T E Q

Inclusive jet production

- This cross section/measurement spans a very wide kinematical range, including the highest transverse momenta (smallest distance scales) of any process
- Note in the cartoon to the right that in addition to the 2->2 hard scatter that we are interested in, we also have to deal with the collision of the remaining constituents of the proton and anti-proton (the "underlying event")
- This has to be accounted for/subtracted for any comparisons of data to pQCD predictions

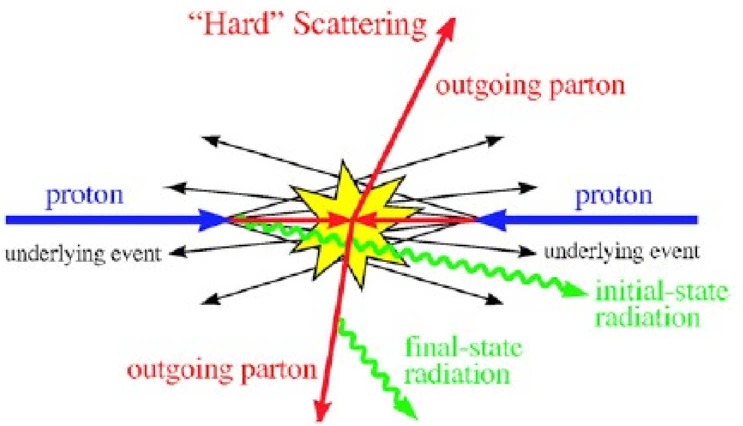
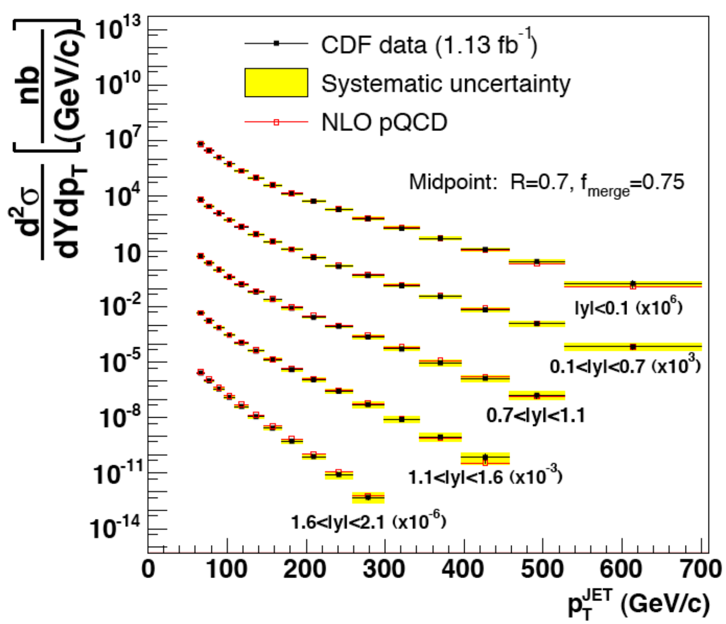


Figure 43. Schematic cartoon of a 2 → 2 hard-scattering event.



CTEQ

Corrections (at the Tevatron)

- Hadron to parton level corrections
  - subtract energy from the jet cone due to the underlying event
  - add energy back due to hadronization
    - partons whose trajectories lie inside the jet cone produce hadrons landing outside
  - the hadronization corrections will be similar at the LHC, while the UE corrections should be much larger
- Result is in good agreement with NLO pQCD predictions using CTEQ6.1 pdf's
  - pdf uncertainty is similar to experimental systematic errors
- Result is also in good agreement with CTEQ6.6

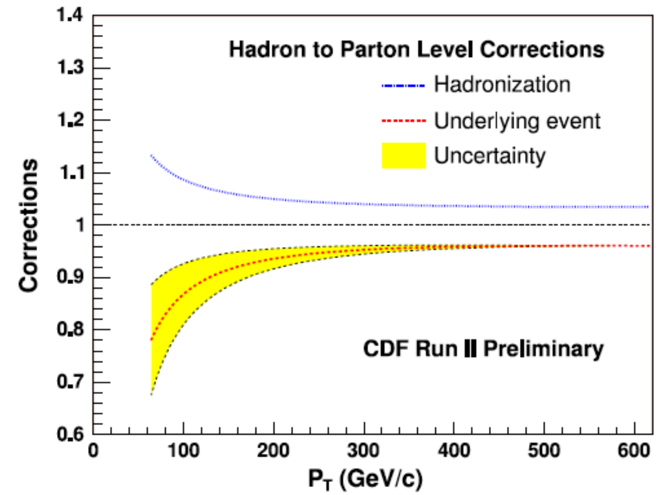


Figure 48. Fragmentation and underlying event corrections for the CDF inclusive jet result, for a cone size $R = 0.7$.

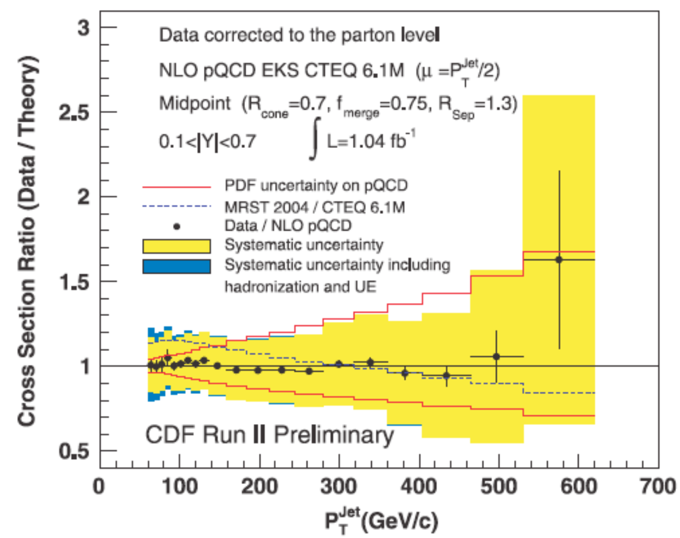
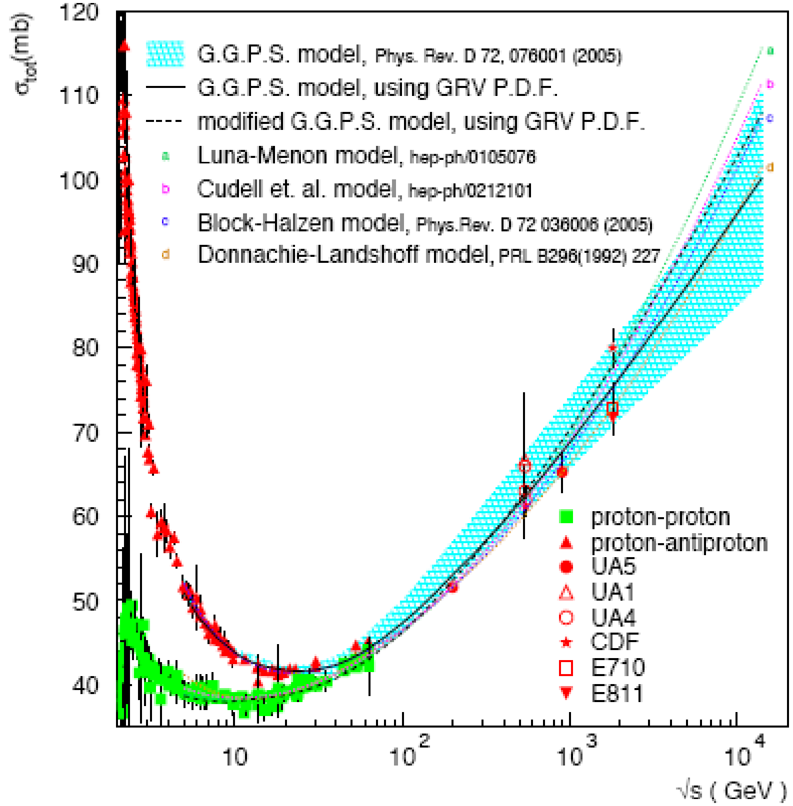


Figure 49. The inclusive jet cross section from CDF in Run 2 compared on a linear scale to NLO theoretical predictions using CTEQ6.1 and MRST2004 pdfs.

Total cross section at LHC (10-14 TeV)

- Fair amount of uncertainty on extrapolation to LHC
  - ln(s) or ln²(s) behavior
  - rely on Roman pot measurements
    - need 90 m optics run; sometime in 2009?
  - extrapolating measured cross section to full inelastic cross section will still have uncertainties (and may take time/analysis)
  - we'll need benchmark cross sections for normalization
- $\sigma_{physics}$ ~ #events/luminosity
- We're not going to know the luminosity very well until we know the total inelastic cross section
- So it's useful to also have some benchmark cross sections for normalization



CTEQ

Precision benchmarks: W/Z cross sections at the LHC

- CTEQ6.1 and MRST NLO predictions in good agreement with each other
- NNLO corrections are small and negative
- NNLO mostly a K-factor; NLO predictions adequate for most predictions at the LHC

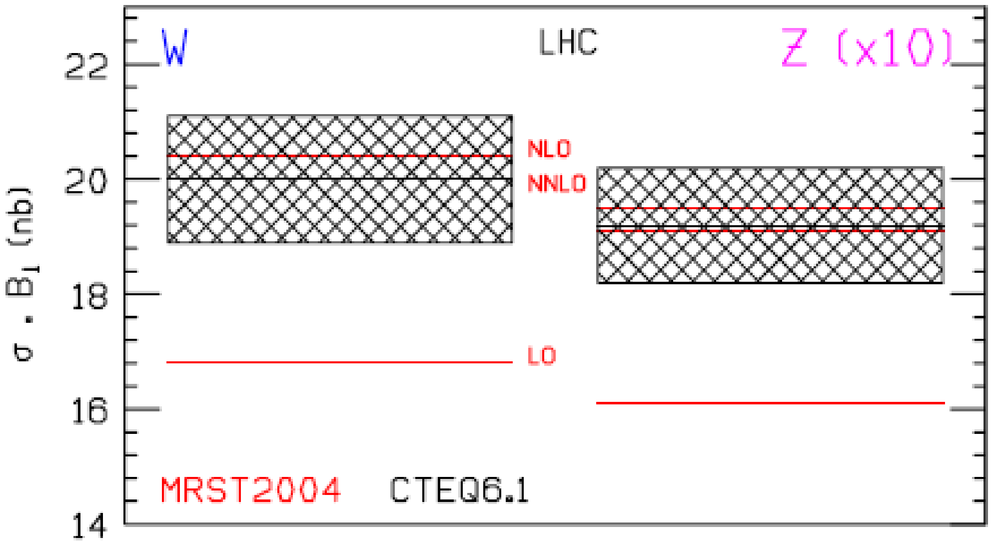


Figure 80. Predicted cross sections for W and Z production at the LHC using MRST2004 and CTEQ6.1 pdfs. The overall pdf uncertainty of the NLO CTEQ6.1 prediction is approximately 5%, consistent with figure 77.

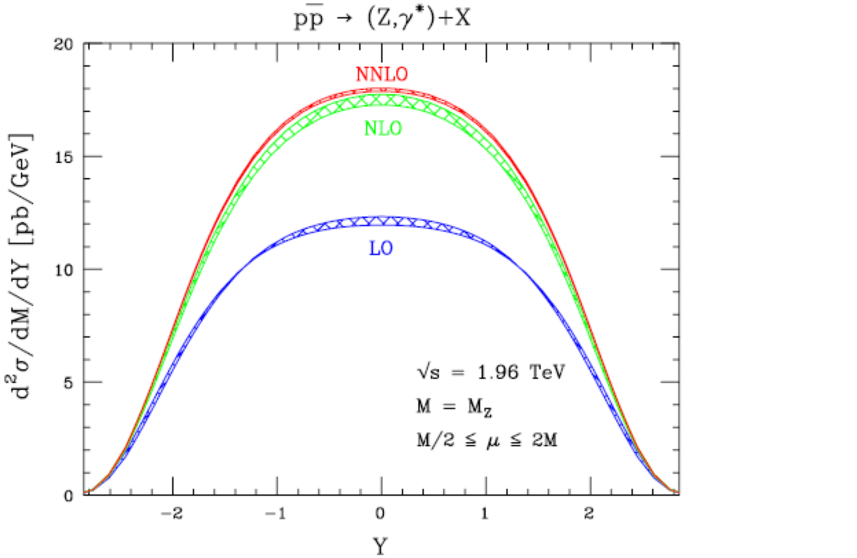
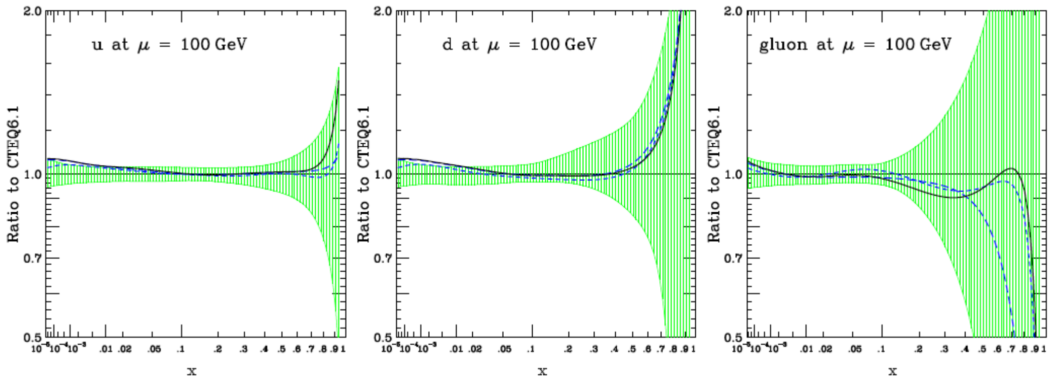


Figure 38. Predictions for the rapidity distribution of an on-shell Z boson in Run 2 at the Tevatron at LO, NLO and NNLO. The bands indicate the variation of the renormalization and factorization scales within the range $M_Z/2$ to $2M_Z$.

C T E Q

Heavy quark mass effects in global fits

- CTEQ6.1 (and previous generations of global fits) used zero-mass VFNS scheme
- With new sets of pdf's (CTEQ6.5/6.6), heavy quark mass effects consistently taken into account in global fitting cross sections and in pdf evolution
- In most cases, resulting pdf's are within CTEQ6.1 pdf error bands
- But not at low x (in range of W and Z production at LHC)
- Heavy quark mass effects only appreciable near threshold
  - ex: prediction for F_2 at low x,Q at HERA smaller if mass of c,b quarks taken into account
  - thus, quark pdf's have to be bigger in this region to have an equivalent fit to the HERA data



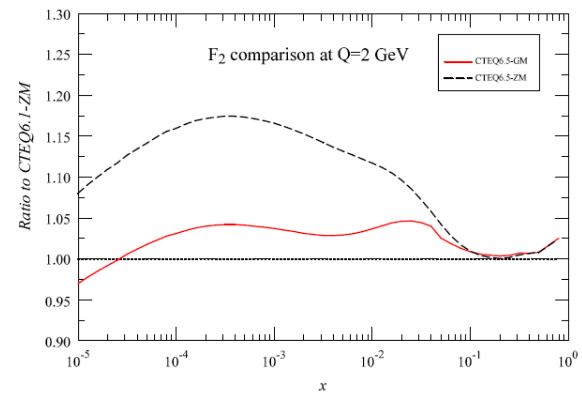


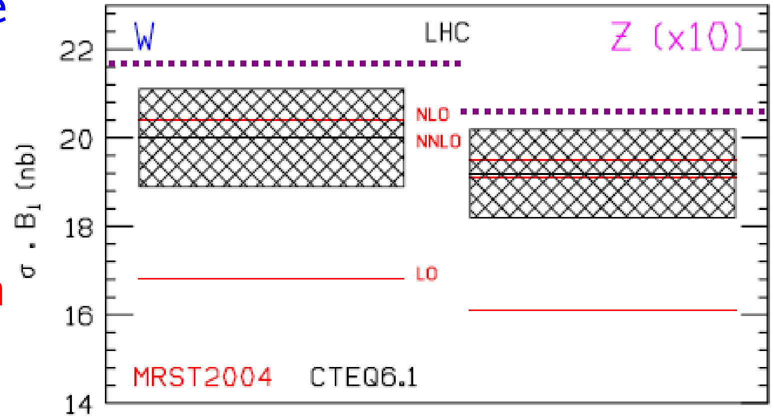
Figure 6: Comparison of theoretical calculations of F_2 using CTEQ6.1M in the ZM formalism (horizontal line of 1.00), CTEQ6.5M in the GM formalism (solid curve), and CTEQ6.5M in the ZM formalism (dashed curve).

implications for LHC phenomenology

CTEQ

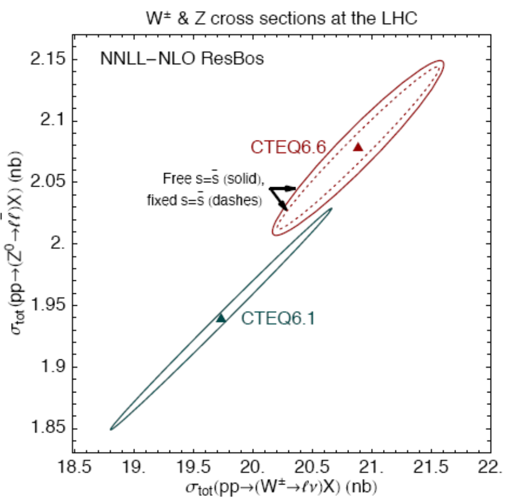
CTEQ6.5(6)

- Inclusion of heavy quark mass effects affects DIS data in x range appropriate for W/Z production at the LHC
- Cross sections for W/Z increase by 6-7%
  - now CTEQ and MRST2004 in disagreement
  - and relative uncertainties of W/Z increase
  - although individual uncertainties of W and Z decrease somewhat
- Two new free parameters in fit dealing with strangeness degrees of freedom so now have 44 error pdf's rather than 40



CTEQ6.5(6)

Figure 80. Predicted cross sections for W and Z production at the LHC using MRST2004 and CTEQ6.1 pdfs. The overall pdf uncertainty of the NLO CTEQ6.1 prediction is approximately 5%, consistent with figure 77.



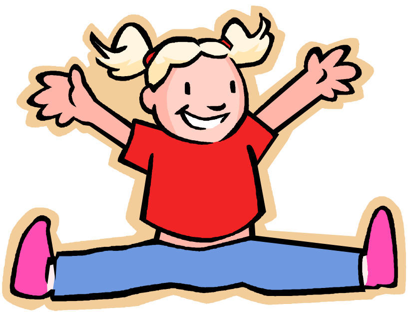
Note importance of strange quark uncertainty for ratio

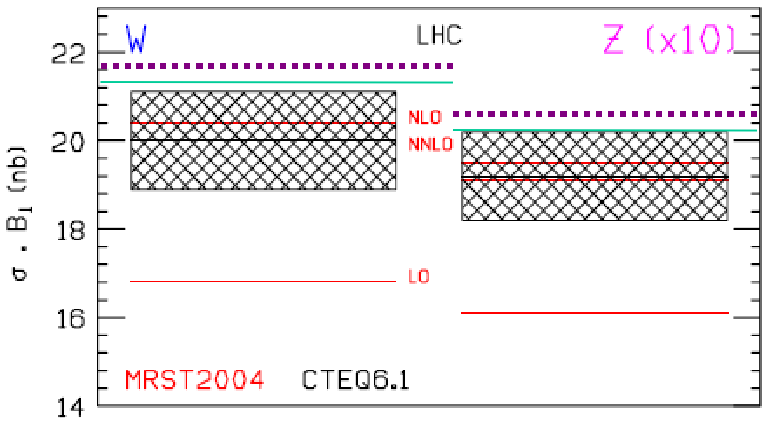
Figure 8: W & Z correlation ellipses at the LHC obtained in the fits with free and fixed strangeness.

CTEQ

…but

- Inclusion of heavy quark mass effects affects DIS data in x range appropriate for W/Z production at the LHC
- …but MSTW2008 has also lead to somewhat increased W/Z cross sections at the LHC
  - now CTEQ6.6 and MSTW2008 in better agreement





CTEQ6.5(6)

MSTW08

Figure 80. Predicted cross sections for W and Z production at the LHC using MRST2004 and CTEQ6.1 pdfs. The overall pdf uncertainty of the NLO CTEQ6.1 prediction is approximately 5%, consistent with figure 77.

C T E Q

Correlations with Z, tT

Define a correlation cosine between two quantities

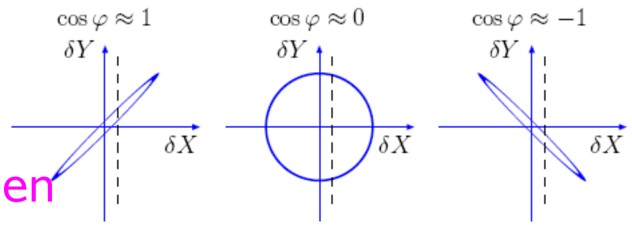
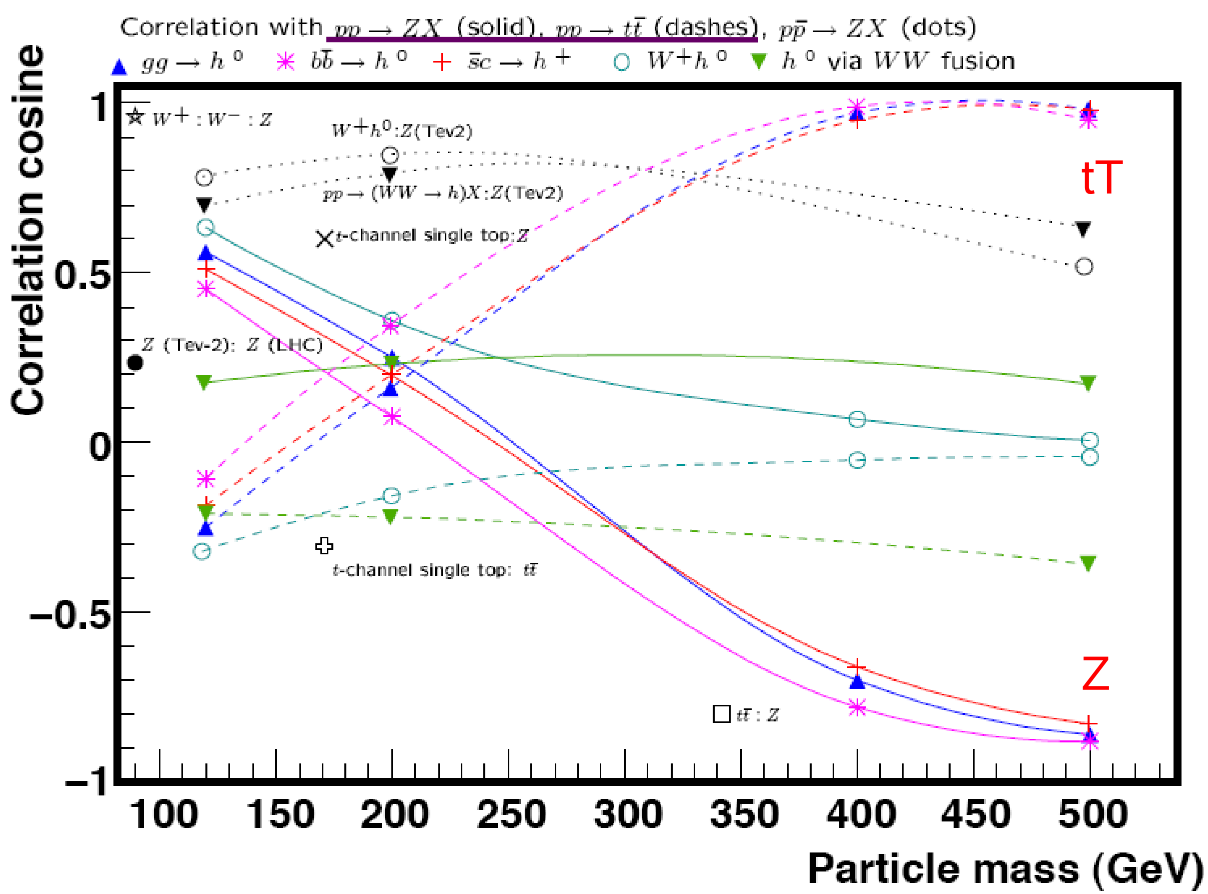


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

- If two cross sections are very correlated, then cosϕ~1
- …uncorrelated, then cosϕ~0
- …anti-correlated, then cosϕ~-1



- Note that correlation curves to Z and to tT are mirror images of each other
- By knowing the pdf correlations, can reduce the uncertainty for a given cross section in ratio to a benchmark cross section **iff** cos ϕ > 0;e.g. $\Delta(\sigma_{W^+}/\sigma_Z)$~1%
- If cos ϕ < 0, pdf uncertainty for one cross section normalized to a benchmark cross section is larger
- So, for gg->H(500 GeV); pdf uncertainty is 4%; $\Delta(\sigma_H/\sigma_Z)$~8%

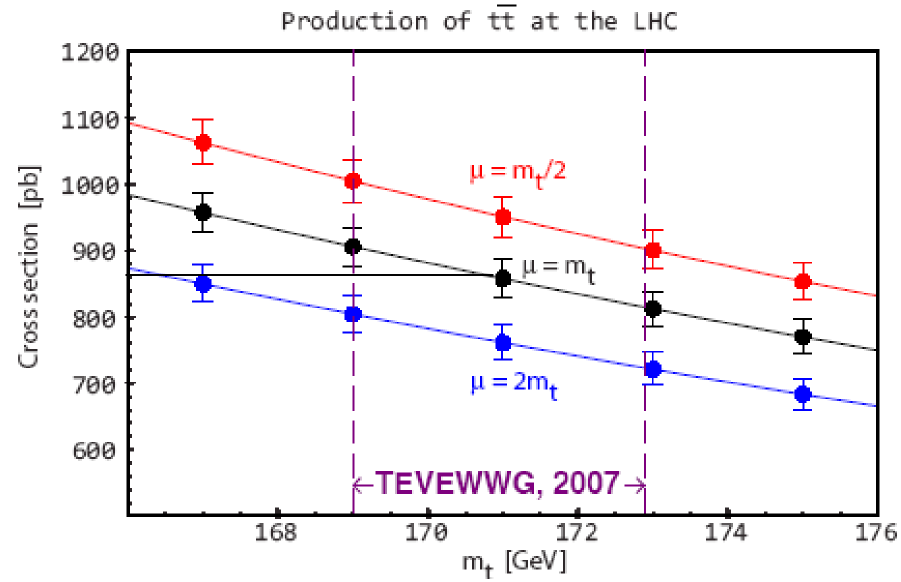
W/Z summary

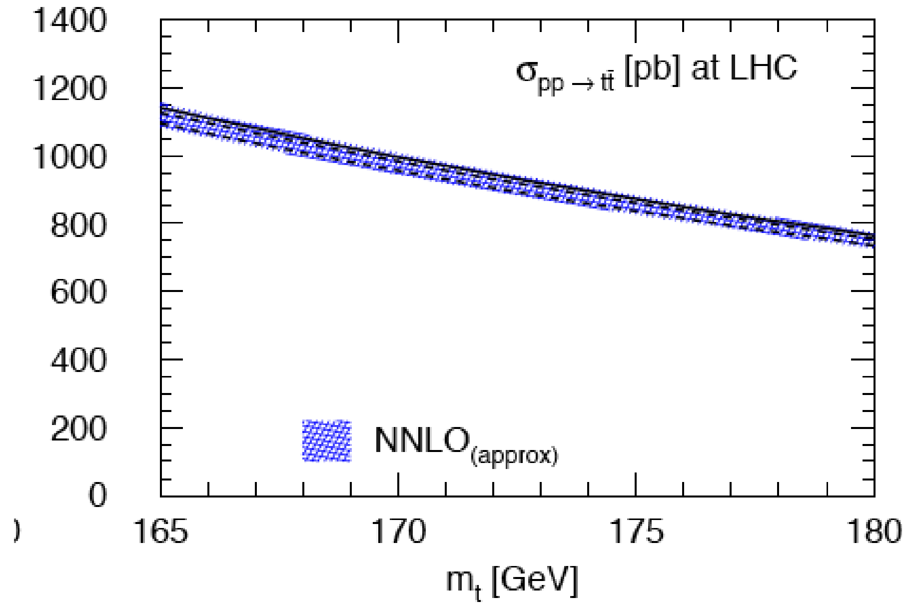
- We will use W and Z cross sections as luminosity normalizations in early running and perhaps always
    - because integrated luminosity is not going to be known much better than 15-20% at first and maybe never better than 5-10%
- The pdf uncertainty for the ratio of a cross section that proceeds with a qQ initial state to the W/Z cross section is significantly reduced
- The pdf uncertainty for the ratio of a cross section that proceeds with a gg initial state to the W/Z cross section is significantly increased
- Would it be reasonable to use tT production as an additional normalization tool?
    - yeah, yeah I know it's difficult

CTEQ

Theory uncertainties for tT at LHC

- Note that at NLO with CTEQ6.6 pdf's the central prediction for the tT cross section for $\mu=m_t$ is ~850 pb (not 800 pb, which it would be if the top mass were 175 GeV); ~880 pb if use effect of threshold resummation
- The scale dependence is around +/-11% and mass dependence is around +/-6%
- Tevatron plans to measure top mass to 1 GeV
  - mass dependence goes to ~+/-3%
- NNLO tT cross section will be finished in (hopefully) near future
  - scale dependence will drop
  - threshold resummation reduces scale dependence to ~3% (Moch and Uwer)
- tT still in worse shape than W/Z, but not by too much
  - and pdf uncertainty is (a bit) smaller

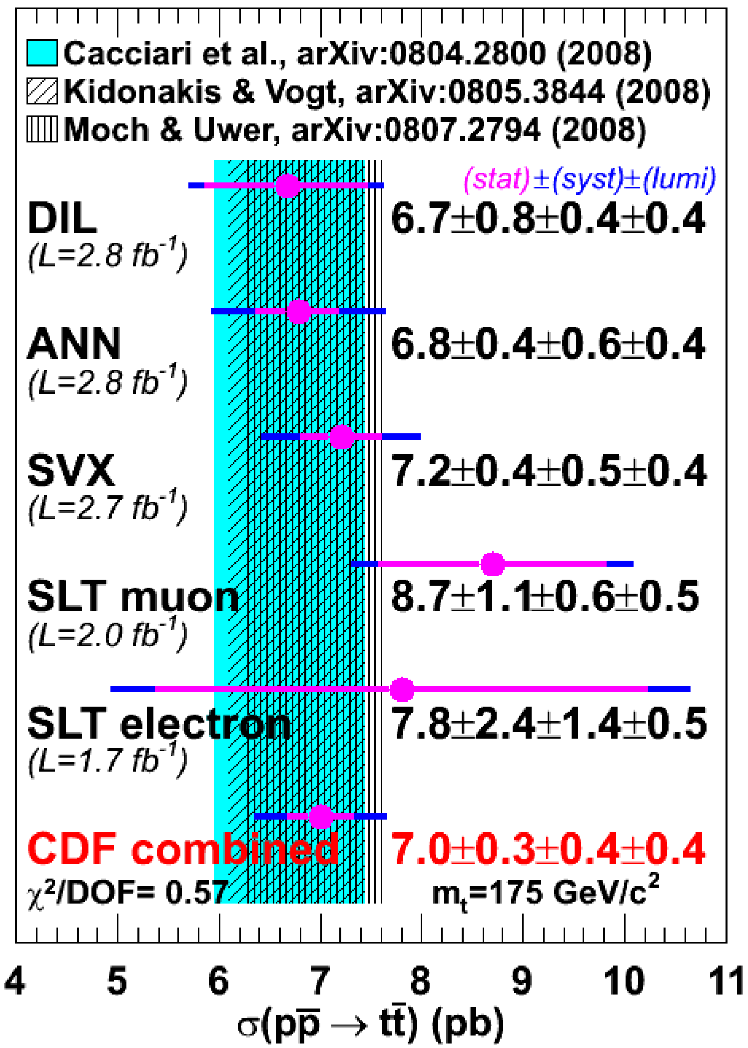




C T E Q

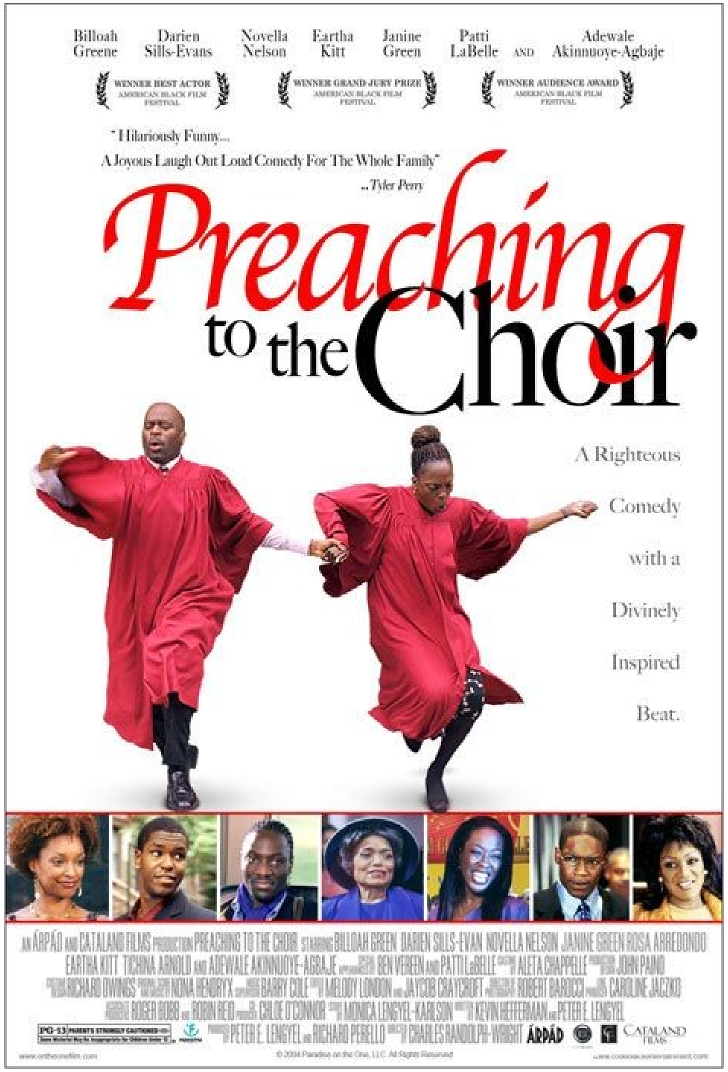
What about experimental uncertainties?

- 10-15% in first year
  - unfortunately, which is where we would most like to have a precise value
- Ultimately, ~5%?
  - dominated by b-tagging uncertainty?
  - systematic errors in common with other complex final states, which may cancel in a ratio?
- Tevatron now does 8% (non-lum)



NLO corrections

- NLO is the first order for which the normalization, and sometimes the shape, is believable
- NLO is necessary for precision comparisons of data to theory
  - for this talk, this is what is known as preaching to the choir (hopefully)
- Sometimes backgrounds to new physics can be extrapolated from non-signal regions, but this is difficult to do for low cross section final states and/or final states where a clear separation of a signal and background region is difficult



CTEQ

NLO corrections

Sometimes it is useful to define a K-factor (NLO/LO). Note the value of the K-factor depends critically on its definition. K-factors at LHC (mostly) similar to those at Tevatron.

	Typical scales		Tevatron K-factor			LHC K-factor		
Process	μ_0	μ_1	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15
W+1jet	m_W	$p_T^{\rm jet}$	1.42	1.20	1.43	1.21	1.32	1.42
W+2jets	m_W	$p_T^{\rm jet}$	1.16	0.91	1.29	0.89	0.88	1.10
WW+jet	m_W	$2m_W$	1.19	1.37	1.26	1.33	1.40	1.42
$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.48
$t\bar{t}$+1jet	m_t	$2m_t$	1.13	1.43	1.37	0.97	1.29	1.10
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51
Higgs	m_H	$p_T^{\rm jet}$	2.33	–	2.33	1.72	–	2.32
Higgs via VBF	m_H	$p_T^{\rm jet}$	1.07	0.97	1.07	1.23	1.34	1.09
Higgs+1jet	m_H	$p_T^{\rm jet}$	2.02	–	2.13	1.47	–	1.90
Higgs+2jets	m_H	$p_T^{\rm jet}$	–	–	–	1.15	–	–

Table 2: K-factors for various processes at the Tevatron and the LHC calculated using a selection of input parameters. In all cases, the CTEQ6M PDF set is used at NLO. $\mathcal{K}$ uses the CTEQ6L1 set at leading order, whilst $\mathcal{K}'$ uses the same set, CTEQ6M, as at NLO. For most of the processes listed, jets satisfy the requirements $p_T > 15$ GeV/c and $|\eta| < 2.5$ (5.0) at the Tevatron (LHC). For Higgs+1,2jets, a jet cut of 40 GeV/c and $|\eta| < 4.5$ has been applied. A cut of $p_T^{\rm jet} > 20$ GeV/c has been applied for the $t\bar{t}$+jet process, and a cut of $p_T^{\rm jet} > 50$ GeV/c for WW+jet. In the W(Higgs)+2jets process the jets are separated by $\Delta R > 0.52$, whilst the VBF calculations are performed for a Higgs boson of mass 120 GeV. In each case the value of the K-factor is compared at two often-used scale choices, where the scale indicated is used for both renormalization and factorization scales.

K-factors may differ from unity because of new subprocesses/ contributions at higher order **and/or differences between LO and NLO pdf's**

Les Houches 2007

C T E Q

Shape dependence of a K-factor

- Inclusive jet production probes very wide x,Q^2 range along with varying mixture of gg,gq,and qq subprocesses
- PDF uncertainties are significant at high p_T
- Over limited range of p_T and y, can approximate effect of NLO corrections by K-factor but not in general
  - in particular note that for forward rapidities, K-factor <<1
  - LO predictions will be large overestimates
  - see extra slides for discussion as to why

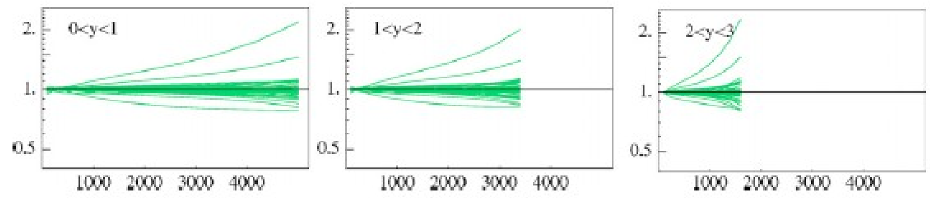


Figure 105. The ratios of the jet cross section predictions for the LHC using the CTEQ6.1 error pdfs to the prediction using the central pdf. The extremes are produced by eigenvector 15.

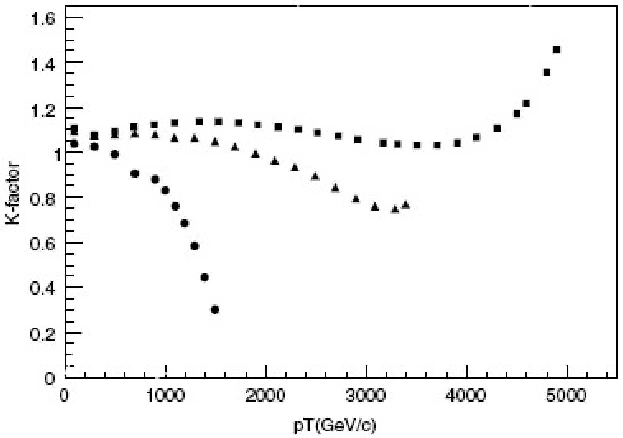
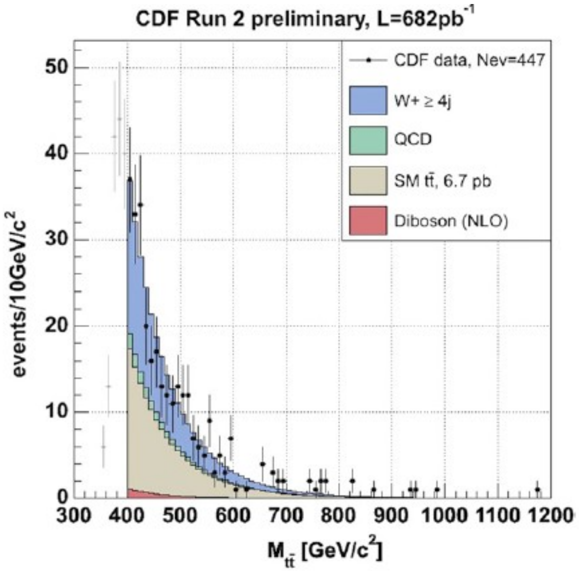


Figure 106. The ratios of the NLO to LO jet cross section predictions for the LHC using the CTEQ6.1 pdfs for the three different rapidity regions (0–1 (squares), 1–2 (triangles), 2–3 (circles)).

CTEQ

Another example, from the Tevatron

- Suppose you measure the high m_{tT} region looking for new physics
- Suppose that your measurement agrees well with Pythia
- Have you missed something?
- Yes, because NLO prediction at high mass is about half of LO prediction
  - partially pdf's
  - partially matrix elements



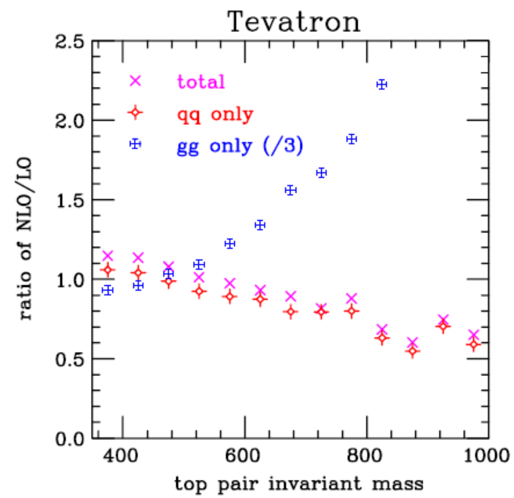


Figure 68. The ratio of the NLO to LO predictions for the $t\bar{t}$ mass at the Tevatron. The predictions include the ratio for the total cross section and for the specific $q\bar{q}$ and gg initial-states. Note that the total also includes a gq contribution (not present at LO) and that the gg ratio is divided by a factor of 3.

CTEQ

What about tT at the LHC?

- The cross section is dominated by the gg subprocess so the K-factor is approximately constant and > 1
  - unlike the Tevatron

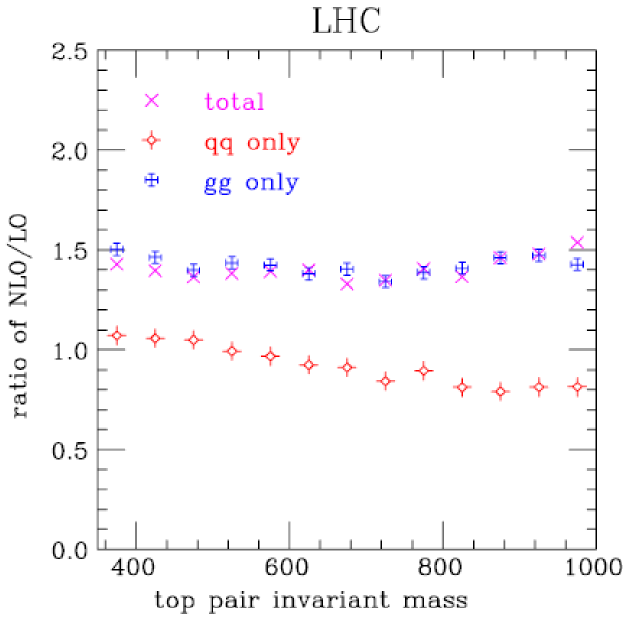


Figure 94. The ratio of the NLO to LO predictions for the $t\bar{t}$ mass at the LHC. The predictions include the ratio for the total cross section and for the specific $q\bar{q}$ and gg initial-states. Note that the total also includes a gq contribution (not present at LO).

C T E Q

NLO calculation priority list from Les Houches 2005: theory benchmarks

G. Heinrich and J. Huston

process ($V \in \{Z, W, \gamma\}$)	relevant for	
1. $pp \to VV$+jet	$t\bar{t}H$, new physics	*
2. $pp \to H + 2$ jets	H production by vector boson fusion (VBF)	*
3. $pp \to t\bar{t}\, b\bar{b}$	$t\bar{t}H$	+
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$	
5. $pp \to VV\, b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics	
6. $pp \to VV + 2$ jets	VBF$\to H \to VV$	
7. $pp \to V + 3$ jets	various new physics signatures	
8. $pp \to VVV$	SUSY trilepton	*+

Table 2. The wishlist of processes for which a NLO calculation is both desired and feasible in the near future.

*completed since list
+people are working

pp->bBbB
pp->4 jets
gg->W*W*

added in 2007

- $pp \to$ VV + jet: One of the most promising channels for Higgs production in the low mass range is through the $H \to WW^*$ channel, with the W's decaying semi-leptonically. It is useful to look both in the $H \to WW$ exclusive channel, along with the $H \to WW$+jet channel. The calculation of $pp \to WW$+jet will be especially important in understanding the background to the latter.
- $pp \to H$+2 jets: A measurement of vector boson fusion (VBF) production of the Higgs boson will allow the determination of the Higgs coupling to vector bosons. One of the key signatures for this process is the presence of forward-backward tagging jets. Thus, QCD production of H + 2 jets must be understood, especially as the rates for the two are comparable in the kinematic regions of interest.
- $pp \to t\bar{t}b\bar{b}$ and $pp \to t\bar{t}$ + 2 jets: Both of these processes serve as background to $t\bar{t}H$, where the Higgs decays into a $b\bar{b}$ pair. The rate for $t\bar{t}jj$ is much greater than that for $t\bar{t}b\bar{b}$ and thus, even if 3 b-tags are required, there may be a significant chance for the heavy flavour mistag of a $t\bar{t}jj$ event to contribute to the background.
- $pp \to VVb\bar{b}$: Such a signature serves as non-resonant background to $t\bar{t}$ production as well as to possible new physics.
- $pp \to$ VV + 2 jets: The process serves as a background to VBF production of Higgs.
- $pp \to$ V + 3 jets: The process serves as background for $t\bar{t}$ production where one of the jets may not be reconstructed, as well as for various new physics signatures involving leptons, jets and missing transverse momentum.
- $pp \to VVV$: The process serves as a background for various new physics subprocesses such as SUSY tri-lepton production.

[23] Process 2 has been calculated since the first version of this list was formulated [138].

What about time lag in going from availability of matrix elements to having a parton level Monte Carlo available? See e.g. H + 2 jets. Other processes are going to be just as complex. What about other processes for which we are theorist/time-limited? What about codes *too complex* for non-experts to run? See CTEQ4LHC

CTEQ

Go back to K-factor table

- Some rules-of-thumb
- NLO corrections are larger for processes in which there is a great deal of color annihilation
  - gg->Higgs
  - gg->$\gamma\gamma$
  - *K*(gg->tT) > *K*(qQ -> tT)
- NLO corrections decrease as more final-state legs are added
  - *K*(gg->Higgs + 2 jets) < *K*(gg->Higgs + 1 jet) < *K*(gg->Higgs)
  - unless can access new initial state gluon channel
- Can we generalize for uncalculated HO processes?
  - so expect K factor for W + 3 jets or Higgs + 3 jets to be reasonably close to 1

Table 1. K-factors for various processes at the Tevatron and the LHC, calculated using a selection of input parameters. In all cases, the CTEQ6M PDF set is used at NLO. $\mathcal{K}$ uses the CTEQ6L1 set at leading order, whilst $\mathcal{K}'$ uses the same set, CTEQ6M, as at NLO. Jets satisfy the requirements $p_T > 15$ GeV and $|\eta| < 2.5$ (5.0) at the Tevatron (LHC). In the $W + 2$ jet process the jets are separated by $\Delta R > 0.52$, whilst the weak boson fusion (WBF) calculations are performed for a Higgs of mass 120 GeV.

	Typical scales		Tevatron K-factor			LHC K-factor		
Process	μ_0	μ_1	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15
$W + 1$ jet	m_W	$\langle p_T^{\rm jet}\rangle$	1.42	1.20	1.43	1.21	1.32	1.42
$W + 2$ jets	m_W	$\langle p_T^{\rm jet}\rangle$	1.16	0.91	1.29	0.89	0.88	1.10
$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.48
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51
Higgs via WBF	m_H	$\langle p_T^{\rm jet}\rangle$	1.07	0.97	1.07	1.23	1.34	1.09

Casimir for biggest color representation final state can be in

Simplistic rule

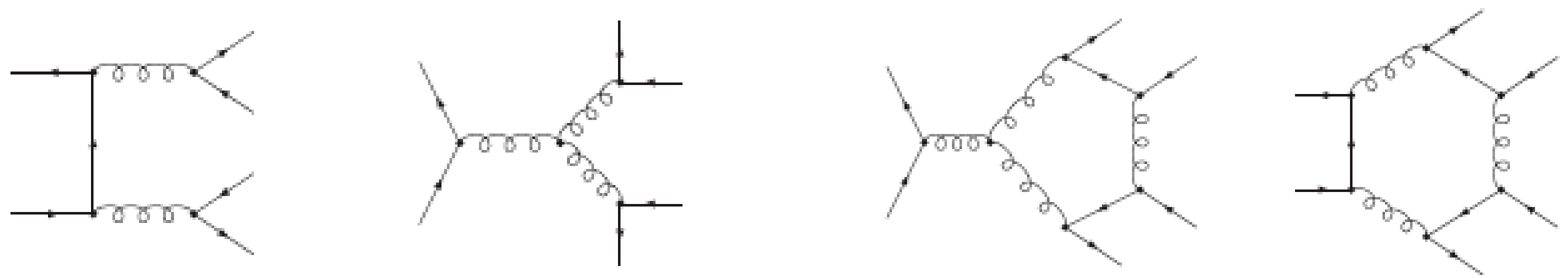
$C_{i1} + C_{i2} - C_{f,max}$

Casimir color factors for initial state

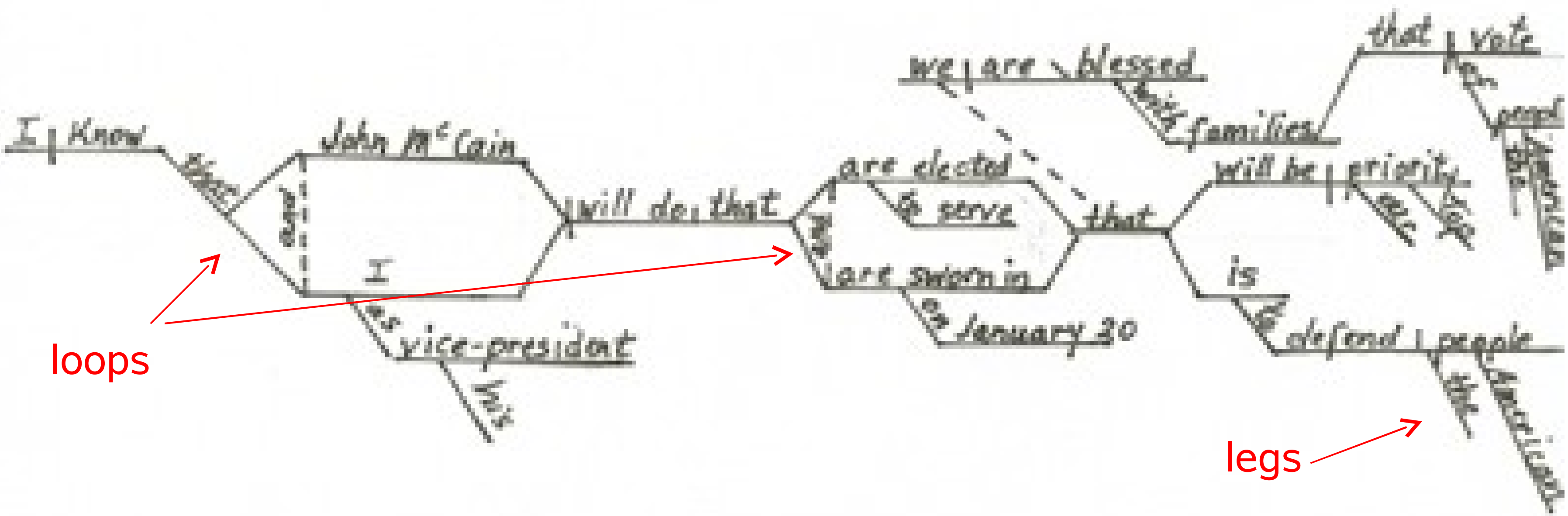
C T E Q

Difficult calculations

I know that the multi-loop and multi-leg calculations are very difficult



but just compare them to the complexity of the sentences that Sarah Palin used in her quest for the vice-presidency.



C T E Q

Some issues/questions

- Once we have the calculations, how do we (experimentalists) use them?
- Best is to have NLO partonic level calculation interfaced to parton shower/hadronization
  - but that has been done only for relatively simple processes and is very (theorist) labor intensive
    - still waiting for inclusive jets in MC@NLO, for example
  - need more automation
- Even with partonic level calculations, need ability to write out ROOT ntuples of parton level events
  - so that can generate once with loose cuts and distributions can be re-made without the need for the lengthy re-running of the predictions
  - what I do for example with MCFM
    - but 10's of Gbytes

C T E Q

CTEQ4LHC/FROOT

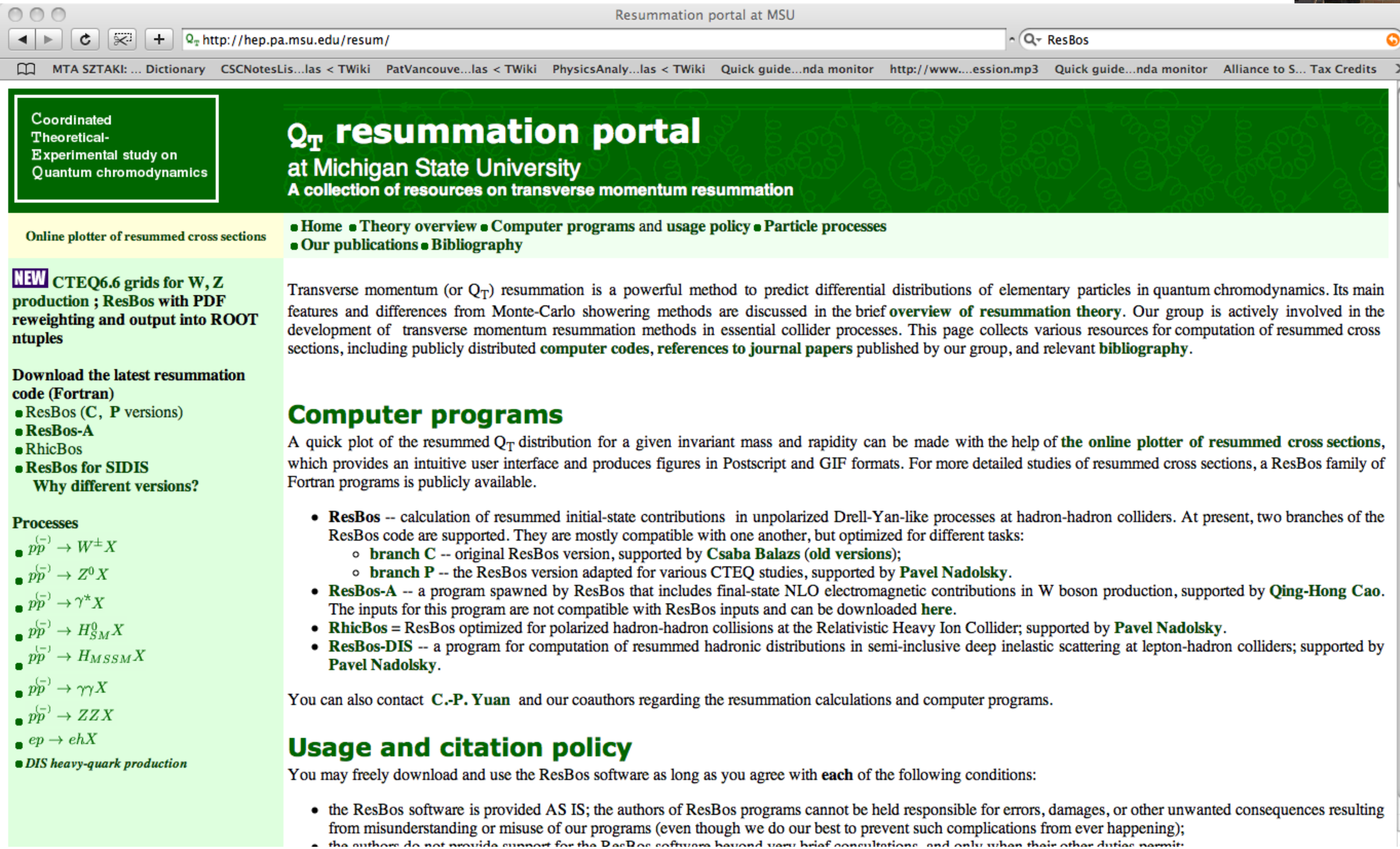
- Collate/create cross section predictions for LHC
  - processes such as W/Z/Higgs(both SM and BSM)/diboson/tT/single top/photons/jets…
  - at LO, NLO, NNLO (where available)
    - new: W/Z production to NNLO QCD and NLO EW
  - pdf uncertainty, scale uncertainty, correlations
  - impacts of resummation (q_T and threshold)
- As prelude towards comparison with actual data
- Using programs such as:
  - MCFM
  - ResBos
  - Pythia/Herwig/Sherpa
  - … private codes with CTEQ
- First on webpage and later as a report

Primary goal: have all theorists (**including you**) write out parton level output into ROOT ntuples
Secondary goal: make libraries of prediction ntuples available

- FROOT: a simple interface for writing Monte-Carlo events into a ROOT ntuple file
- Written by Pavel Nadolsky (nadolsky@physics.smu.edu)
- CONTENTS
- ========
- froot.c -- the C file with FROOT functions
- taste_froot.f -- a sample Fortran program writing 3 events into a ROOT ntuple
- taste_froot0.c -- an alternative top-level C wrapper (see the compilation notes below)
- Makefile

CTEQ

ResBos



Resummation portal at MSU

http://hep.pa.msu.edu/resum/

ResBos

MTA SZTAKI: ... Dictionary | CSCNotesLis...las < TWiki | PatVancouve...las < TWiki | PhysicsAnaly...las < TWiki | Quick guide...nda monitor | http://www....ession.mp3 | Quick guide...nda monitor | Alliance to S... Tax Credits

Coordinated Theoretical-Experimental study on Quantum chromodynamics

Q_T resummation portal

at Michigan State University

A collection of resources on transverse momentum resummation

Online plotter of resummed cross sections

- **Home** • **Theory overview** • **Computer programs** and **usage policy** • **Particle processes**
- **Our publications** • **Bibliography**

NEW **CTEQ6.6 grids for W, Z production ; ResBos with PDF reweighting and output into ROOT ntuples**

Download the latest resummation code (Fortran)

- ResBos (**C**, **P** versions)
- **ResBos-A**
- RhicBos
- **ResBos for SIDIS**

Why different versions?

Processes

- $p\overset{(-)}{p} \to W^{\pm}X$
- $p\overset{(-)}{p} \to Z^0 X$
- $p\overset{(-)}{p} \to \gamma^* X$
- $p\overset{(-)}{p} \to H^0_{SM} X$
- $p\overset{(-)}{p} \to H_{MSSM} X$
- $p\overset{(-)}{p} \to \gamma\gamma X$
- $p\overset{(-)}{p} \to ZZX$
- $ep \to ehX$
- ***DIS heavy-quark production***

Transverse momentum (or Q_T) resummation is a powerful method to predict differential distributions of elementary particles in quantum chromodynamics. Its main features and differences from Monte-Carlo showering methods are discussed in the brief **overview of resummation theory**. Our group is actively involved in the development of transverse momentum resummation methods in essential collider processes. This page collects various resources for computation of resummed cross sections, including publicly distributed **computer codes**, **references to journal papers** published by our group, and relevant **bibliography**.

Computer programs

A quick plot of the resummed Q_T distribution for a given invariant mass and rapidity can be made with the help of **the online plotter of resummed cross sections**, which provides an intuitive user interface and produces figures in Postscript and GIF formats. For more detailed studies of resummed cross sections, a ResBos family of Fortran programs is publicly available.

- **ResBos** -- calculation of resummed initial-state contributions in unpolarized Drell-Yan-like processes at hadron-hadron colliders. At present, two branches of the ResBos code are supported. They are mostly compatible with one another, but optimized for different tasks:
  - **branch C** -- original ResBos version, supported by **Csaba Balazs** (**old versions**);
  - **branch P** -- the ResBos version adapted for various CTEQ studies, supported by **Pavel Nadolsky**.
- **ResBos-A** -- a program spawned by ResBos that includes final-state NLO electromagnetic contributions in W boson production, supported by **Qing-Hong Cao**. The inputs for this program are not compatible with ResBos inputs and can be downloaded **here**.
- **RhicBos** = ResBos optimized for polarized hadron-hadron collisions at the Relativistic Heavy Ion Collider; supported by **Pavel Nadolsky**.
- **ResBos-DIS** -- a program for computation of resummed hadronic distributions in semi-inclusive deep inelastic scattering at lepton-hadron colliders; supported by **Pavel Nadolsky**.

You can also contact **C.-P. Yuan** and our coauthors regarding the resummation calculations and computer programs.

Usage and citation policy

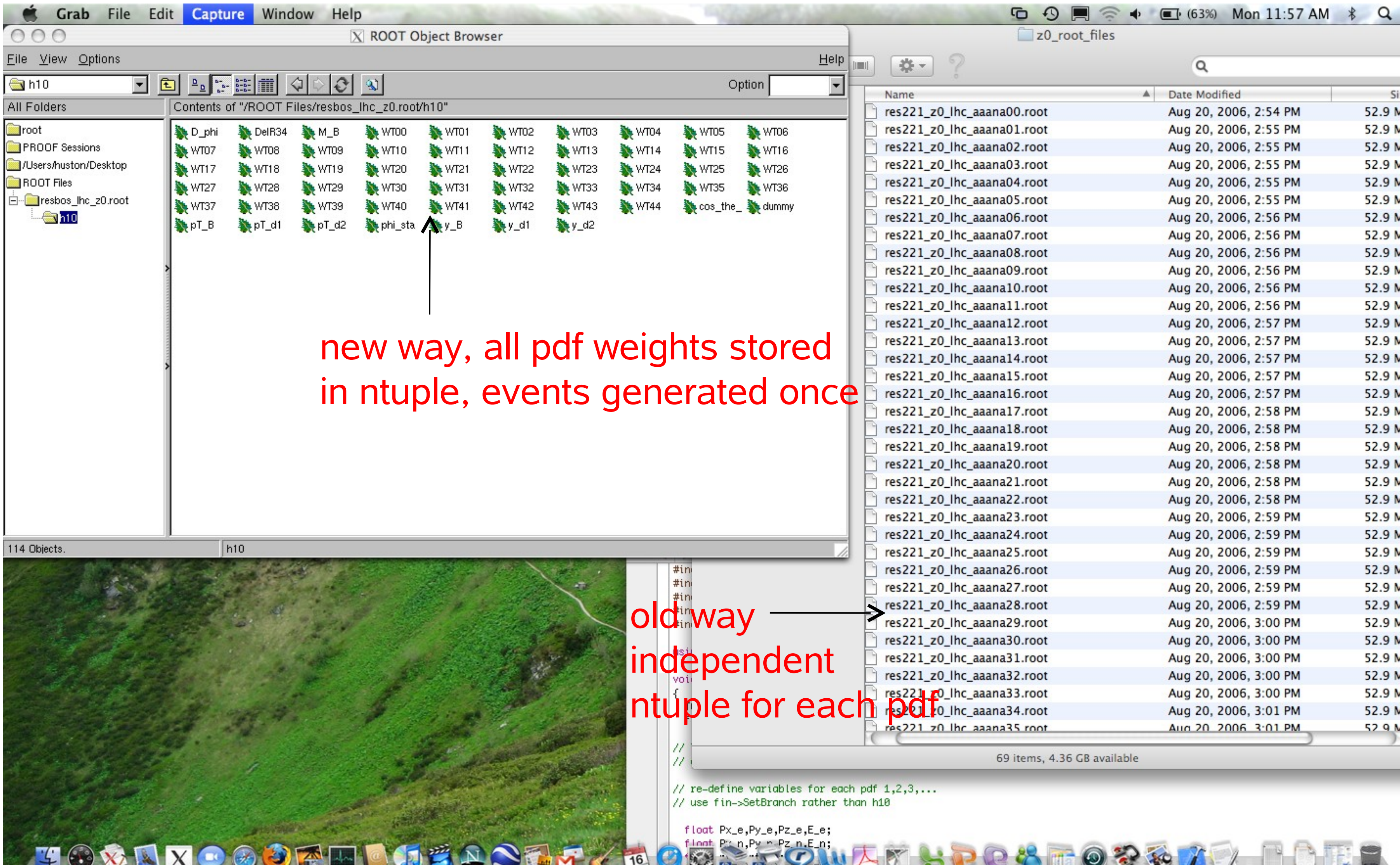
You may freely download and use the ResBos software as long as you agree with **each** of the following conditions:

- the ResBos software is provided AS IS; the authors of ResBos programs cannot be held responsible for errors, damages, or other unwanted consequences resulting from misunderstanding or misuse of our programs (even though we do our best to prevent such complications from ever happening);
- the authors do not provide support for the ResBos software beyond very brief consultations, and only when their other duties permit;

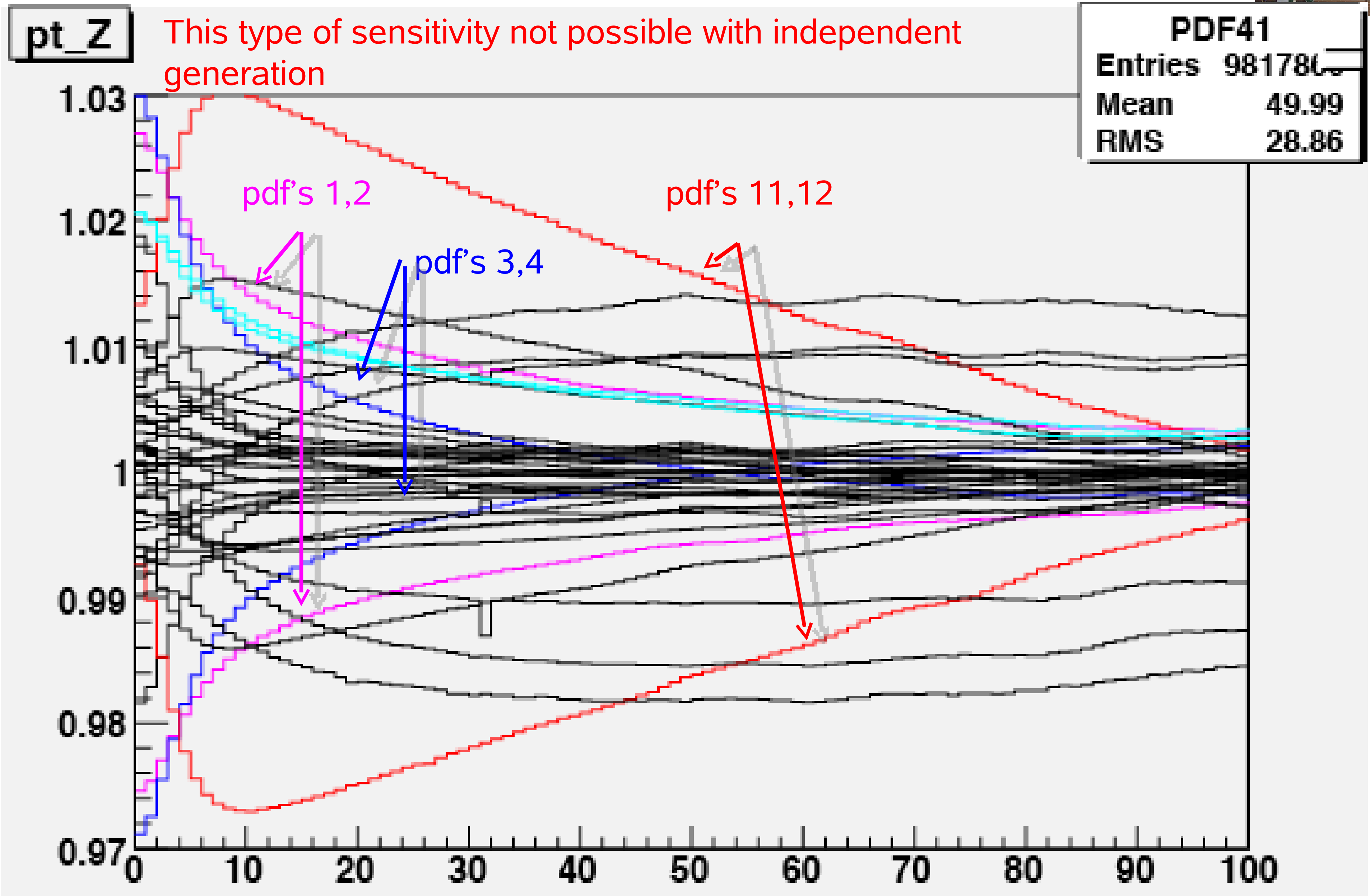
C T E Q

PDF Uncertainties and FROOT

Z production in ResBos



Ratio of Z p_T distributions to that from CTEQ6.6



C T E Q

MCFM

MCFM – Monte Carlo for FeMtobarn processes

http://mcfm.fnal.gov/

MCFM

Resummation...tal at MSU | MTA SZTAKI: ... Dictionary | CSCNotesLis...las < TWiki | PatVancouve...las < TWiki | PhysicsAnaly...las < TWiki | Quick guide...nda monitor | http://www....ession.mp3 | Quick guide...nda monitor

MCFM - Monte Carlo for FeMtobarn processes

Authors: John Campbell, Keith Ellis.

Overview | Examples | Recent progress | Download | Related code | Alternatives

Overview

This is the homepage for the Monte Carlo simulation MCFM. The program is designed to calculate cross-sections for various femtobarn-level processes at hadron-hadron colliders. For most processes, matrix elements are included at next-to-leading order and incorporate full spin correlations. For more details, including a list of available processes, view the documentation in postscript or pdf format.

Examples

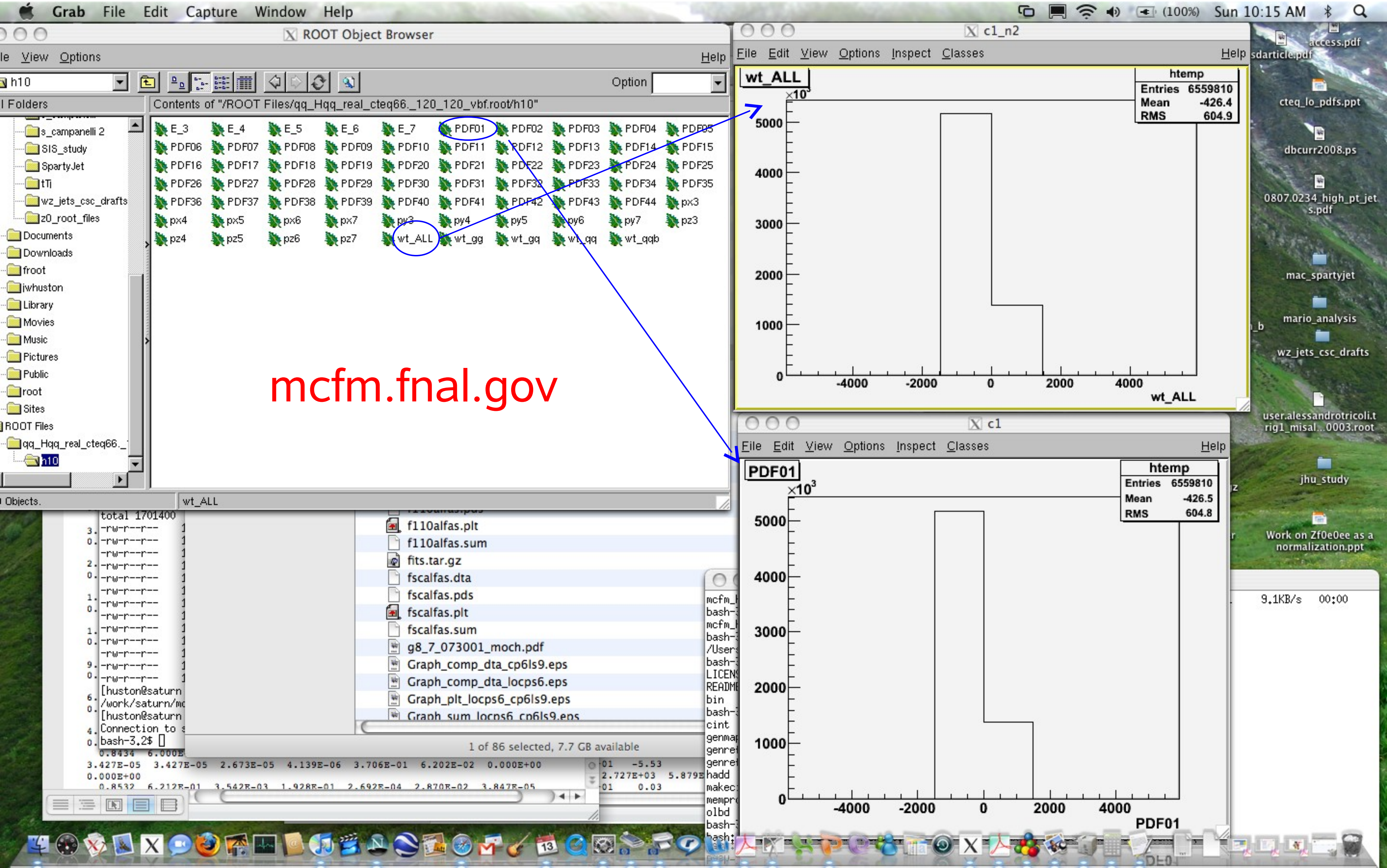
There have been a number of papers based on results produced by the MCFM code, each one corresponding to different processes.

- Calculation of the Wbb background to a WH signal at the Tevatron.
  R.K. Ellis, Sinisa Veseli, Phys. Rev. D60:011501 (1999), hep-ph/9810489.
- Vector boson pair production at the Tevatron, including all spin correlations of the boson decay products.
  J.M. Campbell, R.K. Ellis, Phys. Rev. D60:113006 (1999), hep-ph/9905386.
- Calculation of the Zbb and other backgrounds to a ZH signal at the Tevatron.
  J.M. Campbell, R.K. Ellis, Phys. Rev. D62:114012 (2000), hep-ph/0006304.
- Next-to-leading order corrections to W+2 jet and Z+2 jet production at hadron colliders.
  John Campbell, R.K. Ellis, Phys. Rev. D65:113007 (2002), hep-ph/0202176.
- Higgs Boson Production in Association with a Single Bottom Quark.
  J. Campbell, R.K. Ellis, F. Maltoni, S. Willenbrock, Phys. Rev. D67:095002 (2003), hep-ph/0204093.
- Next-to-Leading Order QCD Predictions for W+2 jet and Z+2 jet Production at the CERN LHC.
  J. Campbell, R.K. Ellis and D. Rainwater, Phys. Rev. D68:094021 (2003), hep-ph/0308195.
- Associated Production of a Z Boson and a Single Heavy Quark Jet.
  J. Campbell, R.K. Ellis, F. Maltoni, S. Willenbrock, Phys. Rev. D69:074021 (2004), hep-ph/0312024.
- Single top production and decay at next-to-leading order,
  J. Campbell, R.K. Ellis and F. Tramontano, Phys.Rev.D70:094012 (2004), hep-ph/0408158.
- Next-to-leading order corrections to Wt production and decay,
  J. Campbell, and F. Tramontano, Nucl.Phys.B726:109-130 (2005), hep-ph/0506289.
- Production of a Z Boson and Two Jets with One Heavy Quark Tag.
  J. Campbell, R.K. Ellis, F. Maltoni, S. Willenbrock, Phys. Rev. D73:054007 (2006), hep-ph/0510362.

The third of these references contains the most details of our method.

C T E Q

MCFM 5.3 has FROOT built in



mcfm.fnal.gov

CTEQ

And don't forget

- NNLO: we need to know some processes (such as inclusive jet production) at NNLO
- Resummation effects: affect important physics signatures
  - mostly taken into account if NLO calculations can be linked with parton showering Monte Carlos

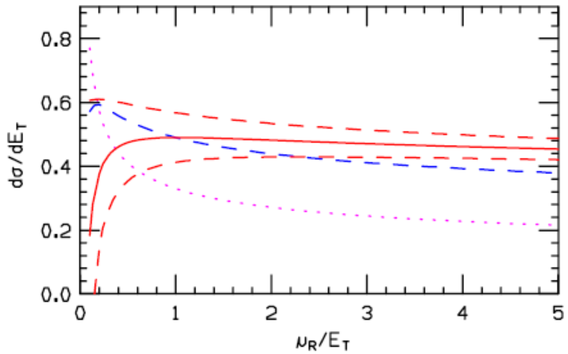


Figure 16. The single jet inclusive distribution at $E_T = 100$ GeV, appropriate for Run I of the Tevatron. Theoretical predictions are shown at LO (dotted magenta), NLO (dashed blue) and NNLO (red). Since the full NNLO calculation is not complete, three plausible possibilities are shown.

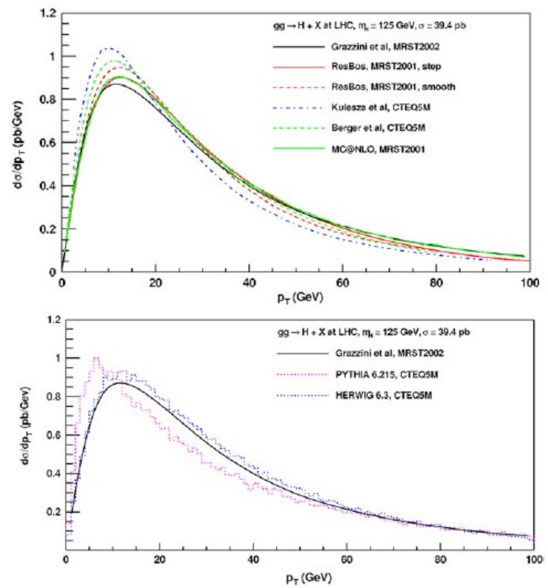


Figure 102. The predictions for the transverse momentum distribution for a 125 GeV mass Higgs boson at the LHC from a number of theoretical predictions. The predictions have all been normalized to the same cross section for shape comparisons. This figure can also be viewed in colour on the benchmark website.

...and

- BFKL logs: will we finally see them at the LHC?

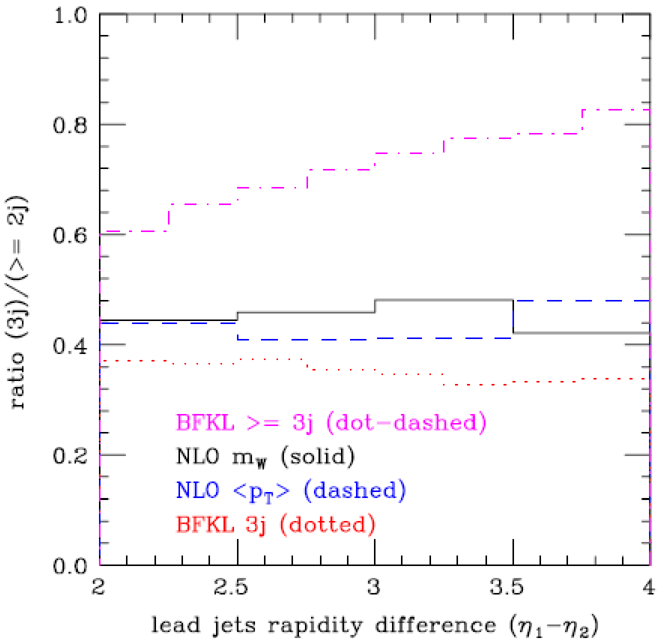
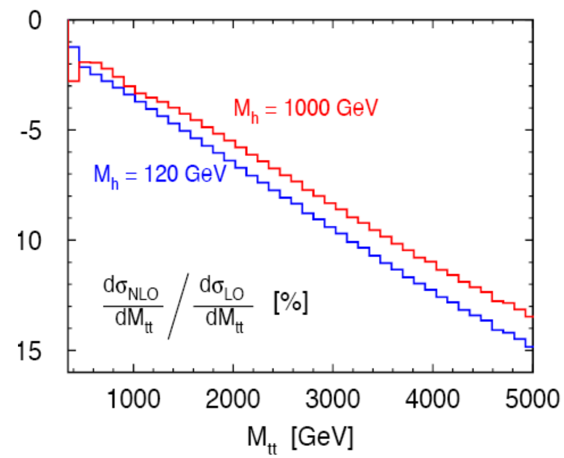


Figure 92. The rate for production of a third (or more) jet in $W+\geqslant 2$ jet events as a function of the rapidity separation of the two leading jets. A cut of 20 GeV has been placed on all jets. Predictions are shown from MCFM using two values for the renormalization and factorization scale, and using the BFKL formalism, requiring either that there be exactly 3 jets or 3 or more jets.

- EW logs: $\alpha_W \log^2(p_T^2/m_W^2)$ can be a big number at the LHC



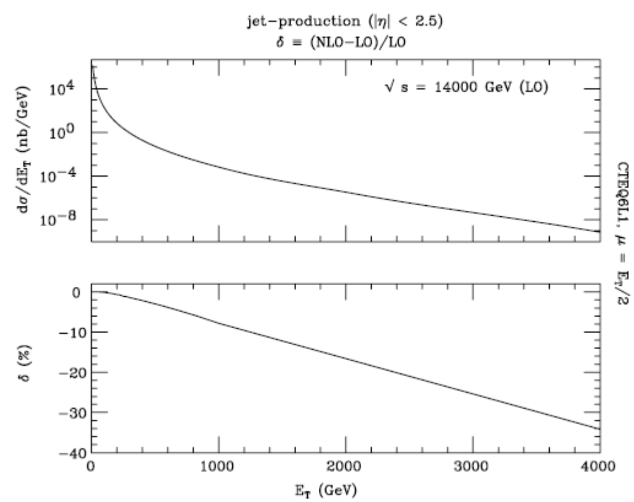


Figure 107. The effect of electroweak logarithms on jet cross sections at the LHC.

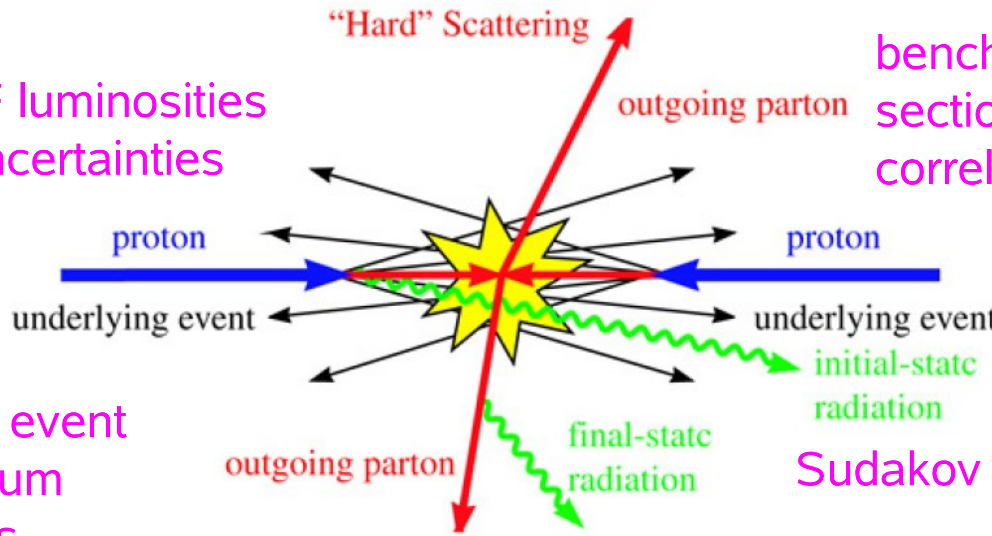
C T E Q

Understanding cross sections at the LHC

LO, NLO and NNLO calculations
K-factors

PDF's, PDF luminosities
and PDF uncertainties

benchmark cross
sections and pdf
correlations



underlying event
and minimum
bias events

Sudakov form factors

jet algorithms and jet reconstruction

Most experimenters are/will still mostly use parton shower Monte Carlo for all predictions/theoretical comparisons at the LHC.

CTEQ

Modified LO pdf's (LO*)

- What about pdf's for parton shower Monte Carlos?
  - standard has been to use LO pdf's, most commonly CTEQ5L/CTEQ6L, in Pythia, Herwig, Sherpa, ALPGEN/Madgraph+…
- …but
  - LO pdf's can create LHC cross sections/acceptances that differ in both shape and normalization from NLO
    - due to influence of HERA data
    - and lack of ln(1/x) and ln(1-x) terms in leading order pdf's and evolution
  - …and are often outside NLO error bands
  - experimenters use the NLO error pdf's in combination with the central LO pdf even with this mis-match
    - causes an error in pdf re-weighting due to non-matching of Sudakov form factors
  - predictions for inclusive observables from LO matrix elements for many of the collider processes that we want to calculate are not so different from those from NLO matrix elements (aside from a reasonably constant K-factor)

Modified LO pdf’s (LO*)

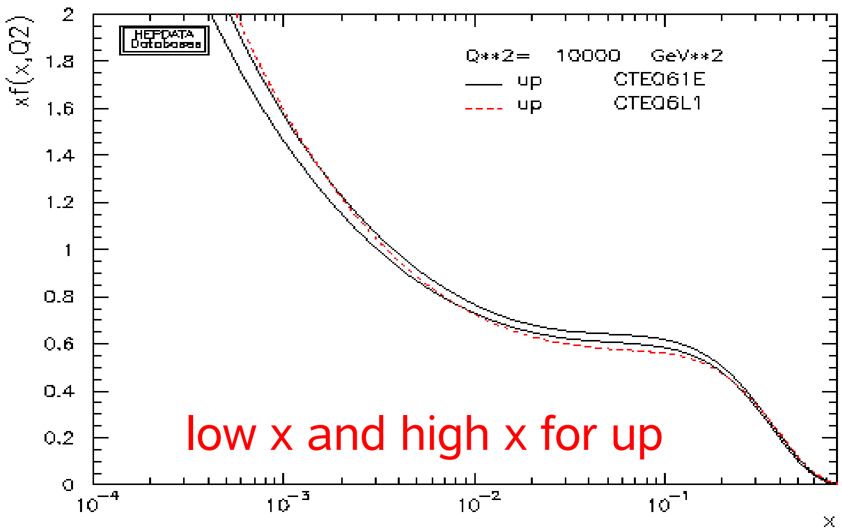
- …but
  - we (and in particular Torbjorn Sjostrand) *like* the low x behavior of LO pdf’s and rely upon them for our models of the underlying event at the Tevatron and its extrapolation to the LHC
  - as well as calculating low x cross sections at the LHC
  - and no one listened to me when I urged the use of NLO pdf’s
- thus, the need for modified LO pdf’s

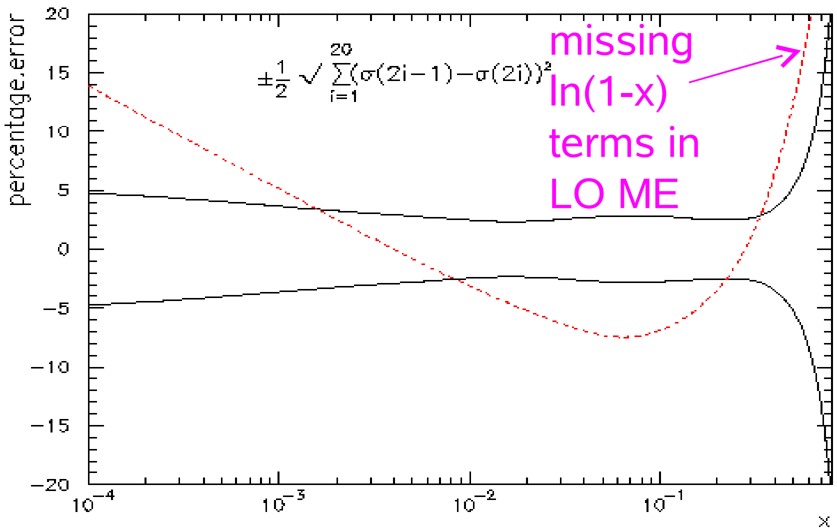
C T E Q

CTEQ talking points

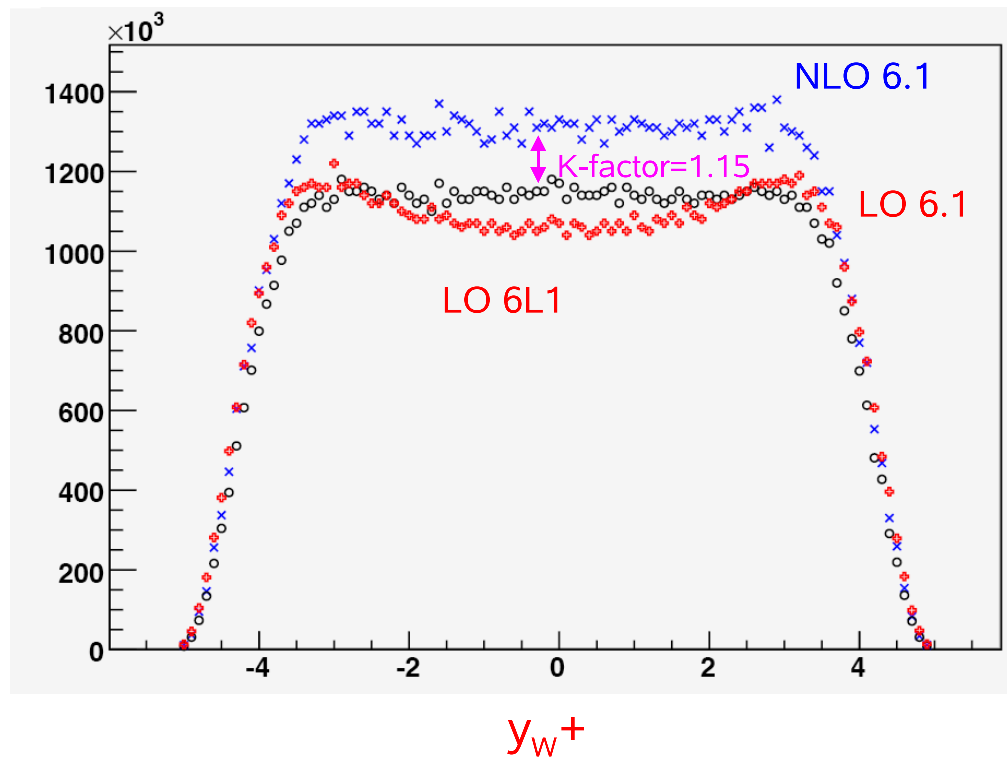
- LO* pdf's should behave as LO as x->0; as close to NLO as possible as x->1
- LO* pdf's should be universal, i.e. results should be reasonable run on any platform with nominal physics scales
- It should be possible to produce error pdf's with
  - similar Sudakov form factors
  - similar UE
  - so pdf re-weighting makes sense
- LO* pdf's should describe underlying event at Tevatron with a tune similar to CTEQ6L (for convenience) and extrapolate to a *reasonable* UE at the LHC

Where are the differences between LO and NLO partons?





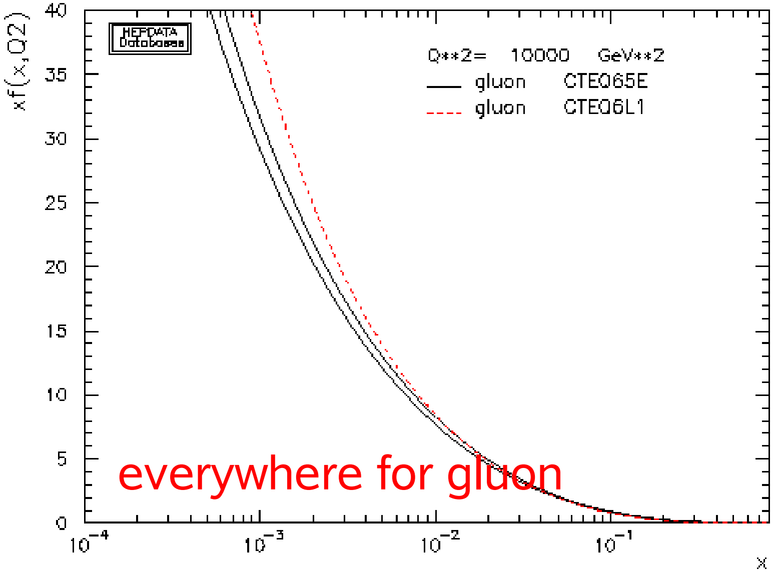
W⁺ rapidity distribution at LHC

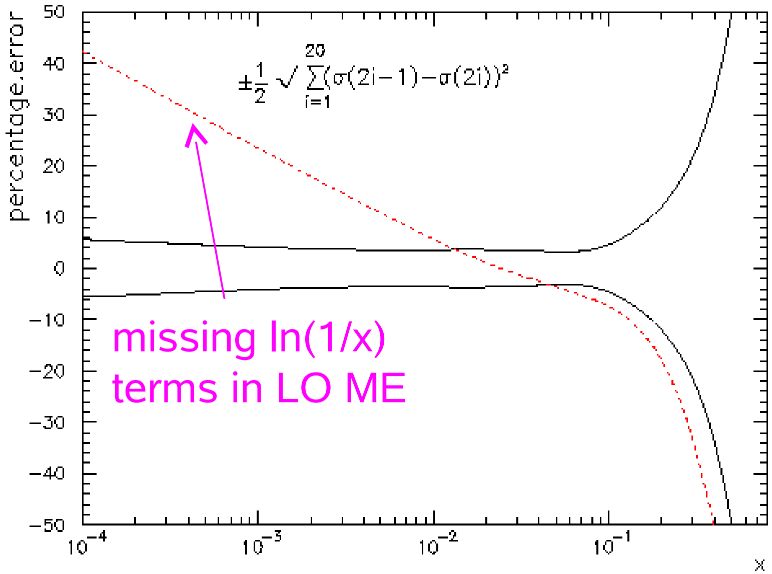


For example, the shape of the W⁺ rapidity distribution is significantly different than the NLO result if the LO pdf is used, but very similar if the NLO pdf is used.

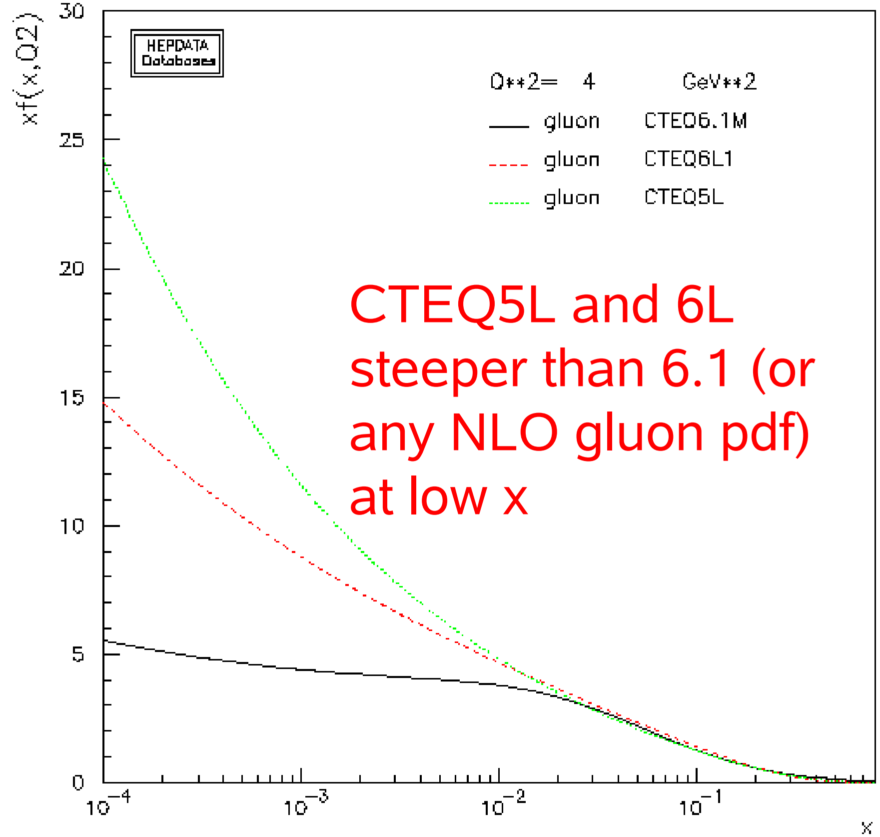
C T E Q

Where are the differences?





- at low Q

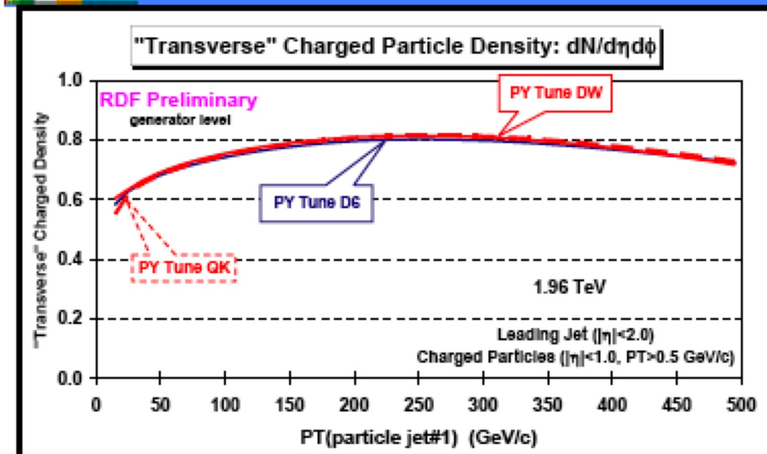


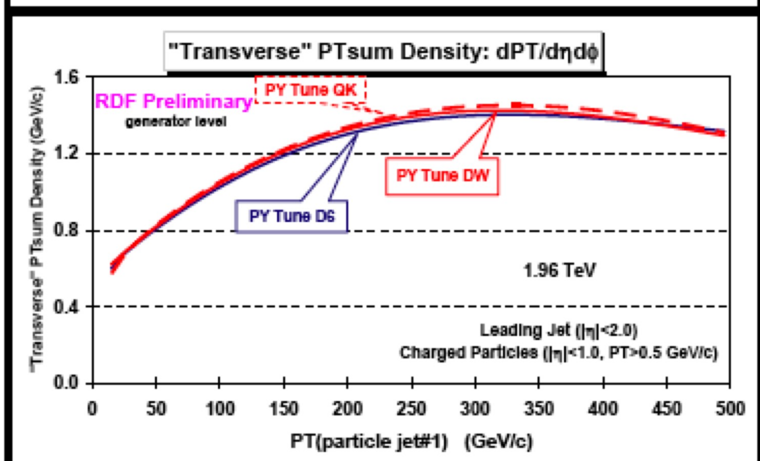
CTEQ

Tunes with CTEQ6L

- Tune A (and derivatives) obtained with CTEQ5L but 6L works just as well

New PYTHIA 6.2 Tunes





	1.96 TeV		14 TeV	
	P_{T0}(MPI) GeV	σ(MPI) mb	P_{T0}(MPI) GeV	σ(MPI) mb
Tune DW	1.9409	351.7	3.1730	549.2
Tune DWT	1.9409	351.7	2.6091	829.1
ATLAS	2.0046	324.5	2.7457	768.0
Tune D6	1.8387	306.3	3.0059	546.1
Tune D6T	1.8387	306.3	2.5184	786.5
Tune QK	1.9409	259.5	3.1730	422.0
Tune QKT	1.9409	259.5	2.6091	588.0

➡ **Average charged particle density and PTsum density in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus P_T(jet#1) at 1.96 TeV for PY Tune DW, Tune D6, and Tune QK.**

C T E Q

CTEQ techniques

- Include in LO* fit (weighted) pseudo-data for characteristic LHC processes produced using CTEQ6.6 NLO pdf's with NLO matrix elements (using MCFM), along with full CTEQ6.6 dataset (2885 points)
  - low mass bB
    - fix low x gluon for UE
  - tT over full mass range
    - higher x gluon
  - W^+,W^-,Z^0 rapidity distributions
    - quark distributions
  - gg->H (120 GeV) rapidity distribution

<u>Choices</u>

- Use of 2-loop or 1-loop α_s
  - Herwig preference for 2-loop
  - Pythia preference for 1-loop
- Fixed momentum sum rule, or not
  - re-arrange momentum within proton and/or add extra momentum
  - extra momentum appreciated by some of pseudo-data sets but not others and may lose some useful correlations
- Fix pseudo-data normalizations to K-factors expected from higher order corrections, or let float
- Scale variation within reasonable range for fine-tuning of agreement with pseudo-data
  - for example, let vector boson scale vary from 0.5 m_B to 2.0 m_B
- Will provide pdf's with several of these options for user

C T E Q

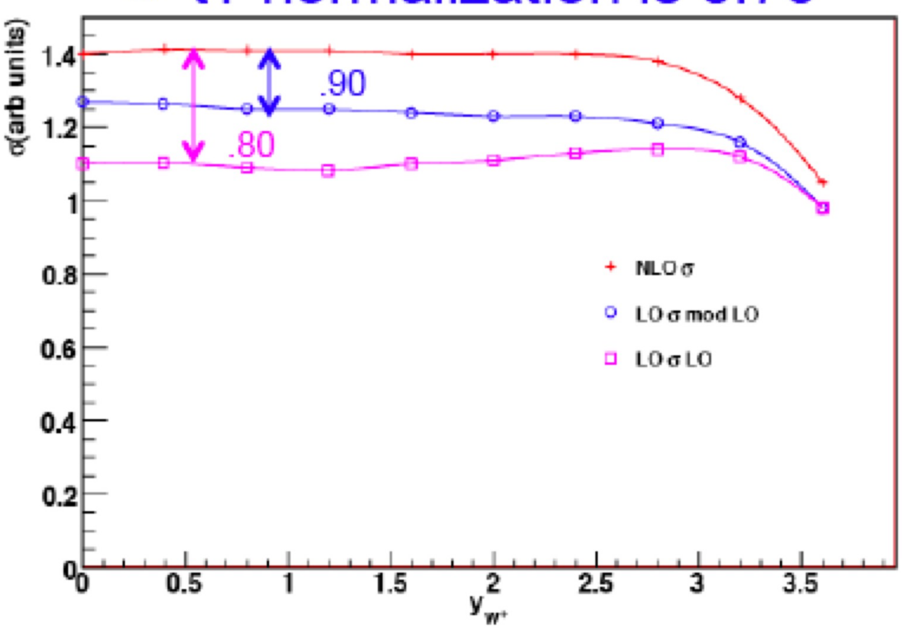
Some observations

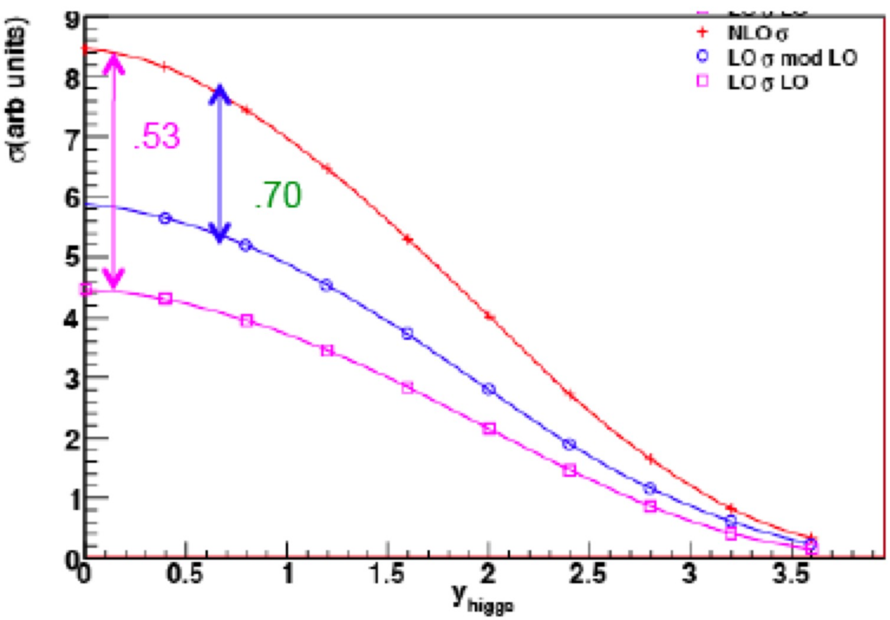
- Pseudo-data has conflicts with global data set
  - that's the motivation of the modified pdf's
- Requiring better fit to pseudo-data increases chisquare of LO fit to global data set (although this is not the primary concern; the fit to the pseudo-data is)
  - χ^2 improves with α_s free in fit
    - no real preference for 1-loop or 2-loop α_s that I can see
  - χ^2 improves with momentum sum rule free
    - prefers more momentum (~1.05)
    - normalization of pseudo-data (needed K-factor) gets closer to 1 (since the chisquare gets better if that happens)
    - still some conflicts with DIS data that don't prefer more momentum

CTEQ

Some results (2-loop α_s)

- Rapidity distributions for W^+ and Higgs from pure NLO, LO with LO pdf, LO with CTEQ modified LO pdf
- Momentum sum=1.06 for CTEQ modified LO pdf
  - why so much less than mod MSTW?
- $\alpha_s(m_Z)$=0.124 for CTEQ modified LO pdf
- tT normalization is 0.76

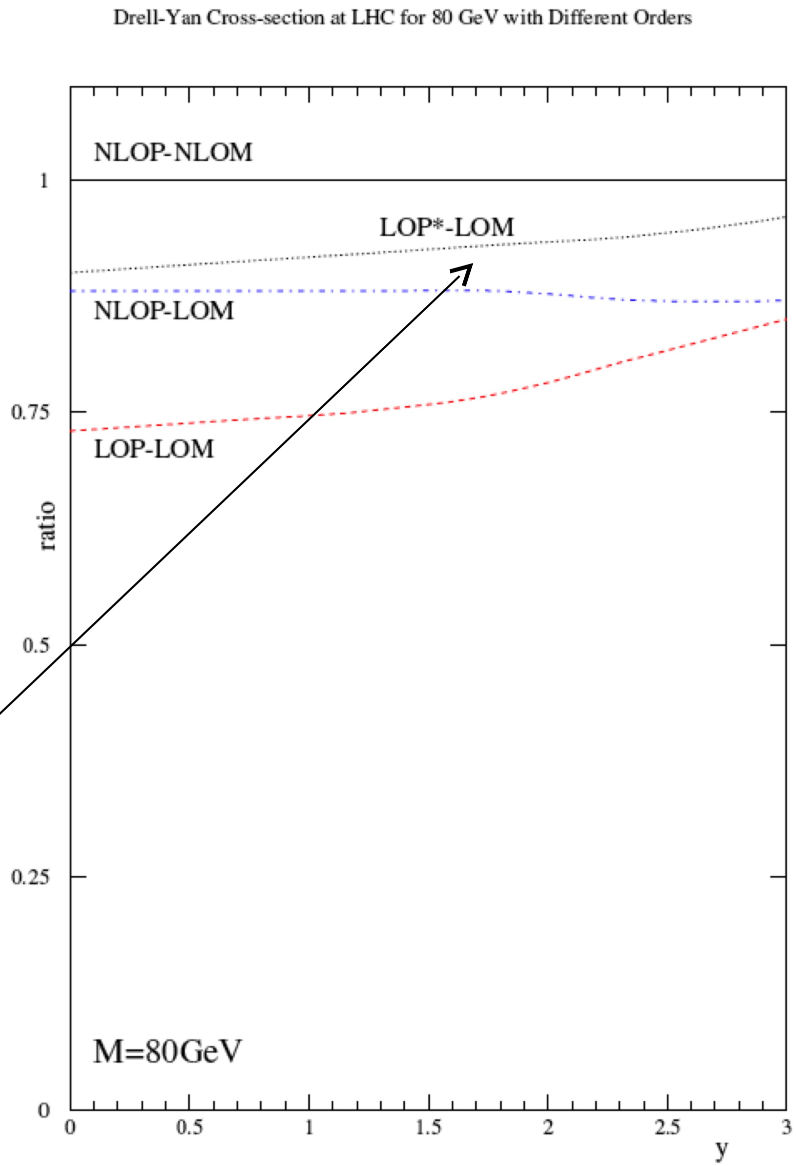




CTEQ

MRSTLO*

- The MRST group has a modified LO pdf that tries to incorporate many of the points mentioned on the previous slides
- They relax the momentum sum rule (114%) and achieve a better agreement (than MRST LO pdf's) with some important LHC benchmark cross sections
- Available in LHAPDF



C T E Q

Error pdf's

- In order to be truly useful, there should be accompanying error pdf's of a similar character as the LO* pdf's
  - so at the least, experimenters will not mix the NLO error pdf's with a central LO pdf
    - but maybe not so bad as far as gluon radiation is concerned if same α_s used
    - would still be a problem for UE if low x gluons are different
- But error pdf's imply a level of precision that is inherent to NLO
  - at NLO, we can construct an orthonormal set of eigenvectors accompanying a level of precision corresponding to a given change of $\Delta\chi^2$ in the global fit
  - that level of $\Delta\chi^2$, that variation, less well defined for LO fits

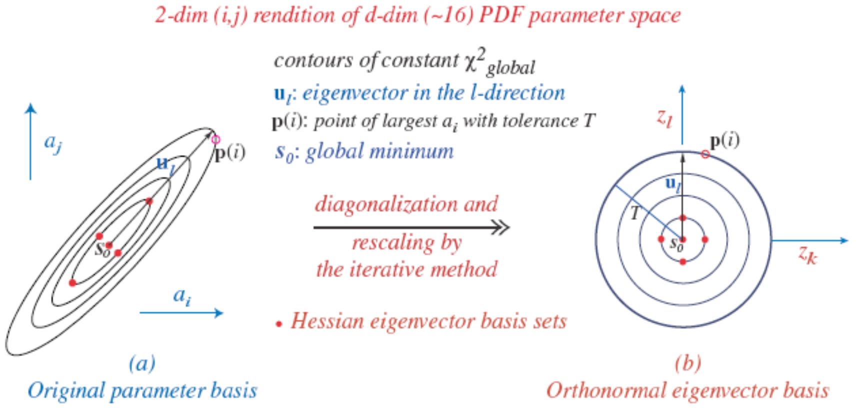


Figure 28. A schematic representation of the transformation from the pdf parameter basis to the orthonormal eigenvector basis.

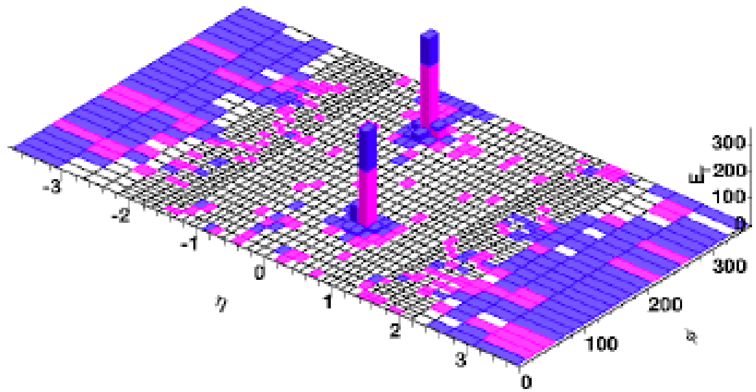
- We are currently working on several ways of implementing this at LO*, but we have not finished stuffing the sausage casings yet

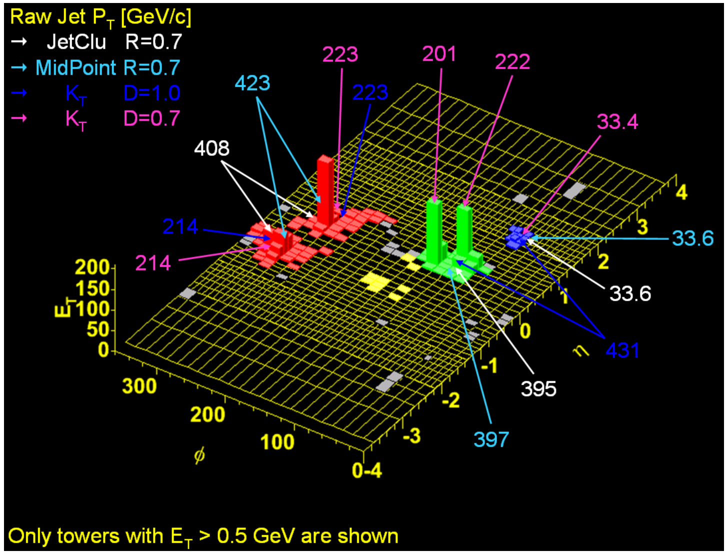
C T E Q

Last but not least: Jet algorithms

- Most of the interesting physics signatures at the LHC involve jets in the final state
- For some events, the jet structure is very clear and there's little ambiguity about the assignment of towers/particles to the jet
- But for other events, there is ambiguity and the jet algorithm must make decisions that impact precision measurements
- There is the tendency to treat jet algorithms as one would electron or photon algorithms
- There's a much more dynamic structure in jet formation that is affected by the decisions made by the jet algorithms and which we can tap in
- Analyses should be performed with multiple jet algorithms, if possible

CDF Run II events





→ SISCone, k_T, anti-k_T (my suggestions)

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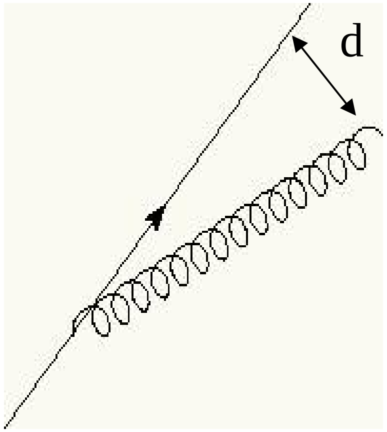
Jet algorithms at NLO

- Remember at LO, 1 parton = 1 jet
- At NLO, there can be two (or more) partons in a jet and life becomes more interesting
- Let's set the p_T of the second parton = z that of the first parton and let them be separated by a distance d (=ΔR)
- Then in regions I and II (on the left), the two partons will be within R_{cone} of the jet centroid and so will be contained in the same jet
    - ~10% of the jet cross section is in Region II; this will decrease as the jet p_T increases (and α_s decreases)
    - at NLO the k_T algorithm corresponds to Region I (for D=R); <u>thus at parton level, the cone algorithm is always larger than the k_T algorithm</u>



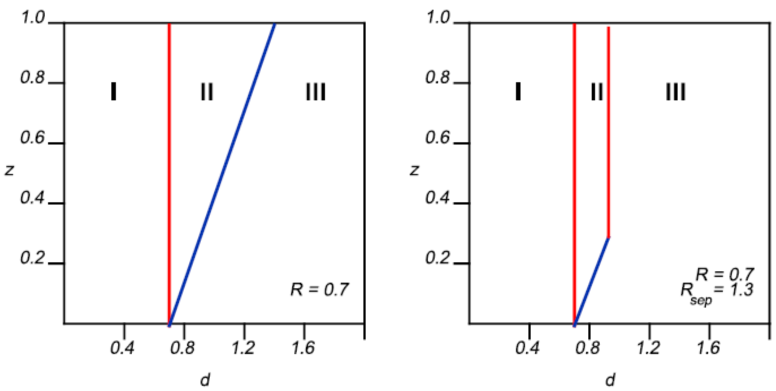


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

In data (and Monte Carlo), jet reconstruction needs more complex algorithms

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Some recommendations from jet paper

- 4-vector kinematics (p_T,y and not E_T,η) should be used to specify jets
- Where possible, analyses should be performed with multiple jet algorithms
- For cone algorithms, split/merge of 0.75 preferred to 0.50

C T E Q

SpartyJet

J. Huston, K. Geerlings
Michigan State University

P-A. Delsart, Grenoble

Sparty

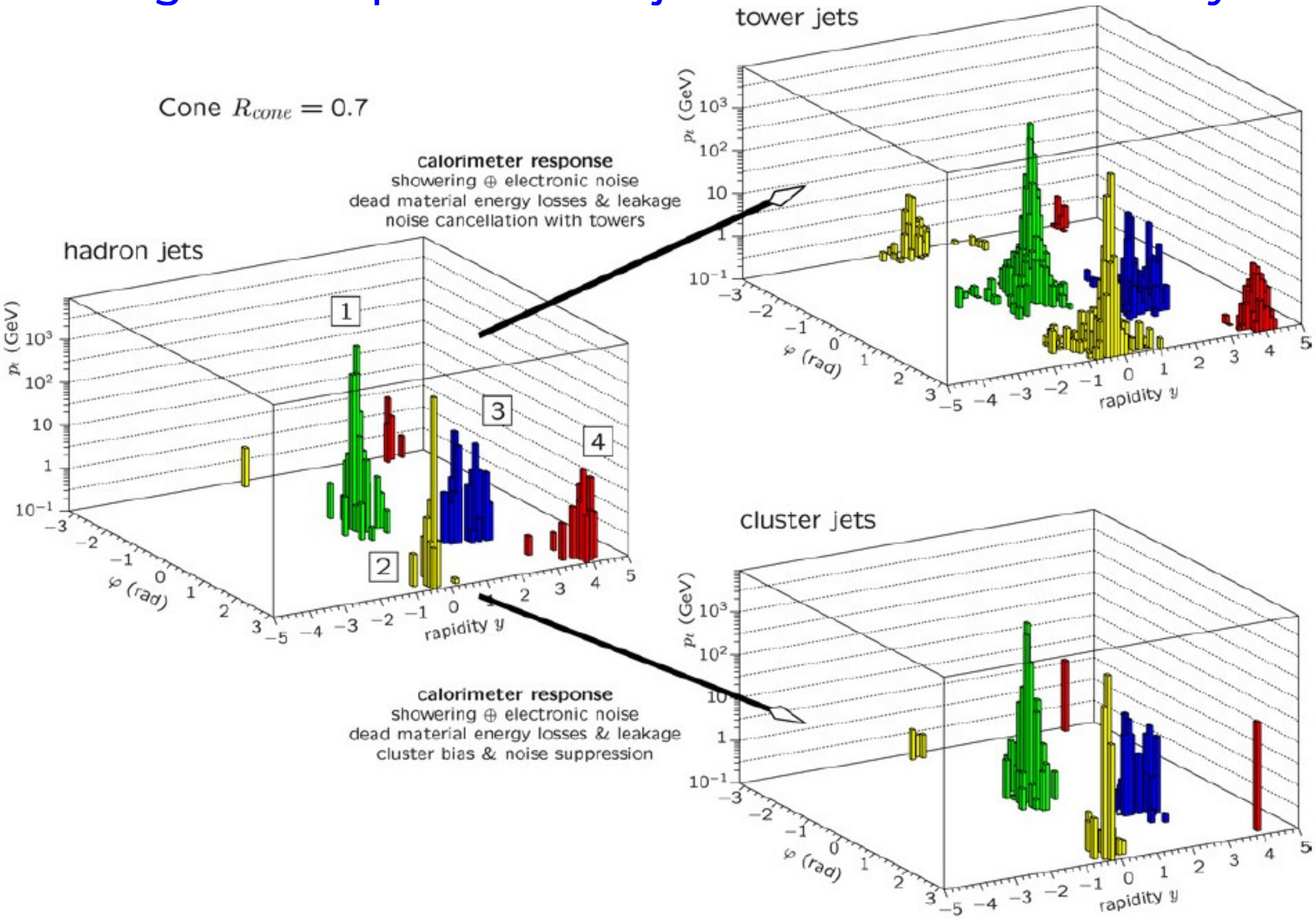
www.pa.msu.edu/~huston/SpartyJet/SpartyJet.html

See also jet review paper.

C T E Q

ATLAS jet reconstruction

- Using calibrated topoclusters, ATLAS has a chance to use jets in a dynamic manner not possible in any previous hadron-hadron calorimeter, i.e. to examine the impact of multiple jet algorithms/parameters/jet substructure on every data set



similar to running at hadron level in Monte Carlos

C T E Q

Inclusive jet cross section

new physics tends to be central

pdf explanations are universal

crucial to measure over a wide rapidity interval

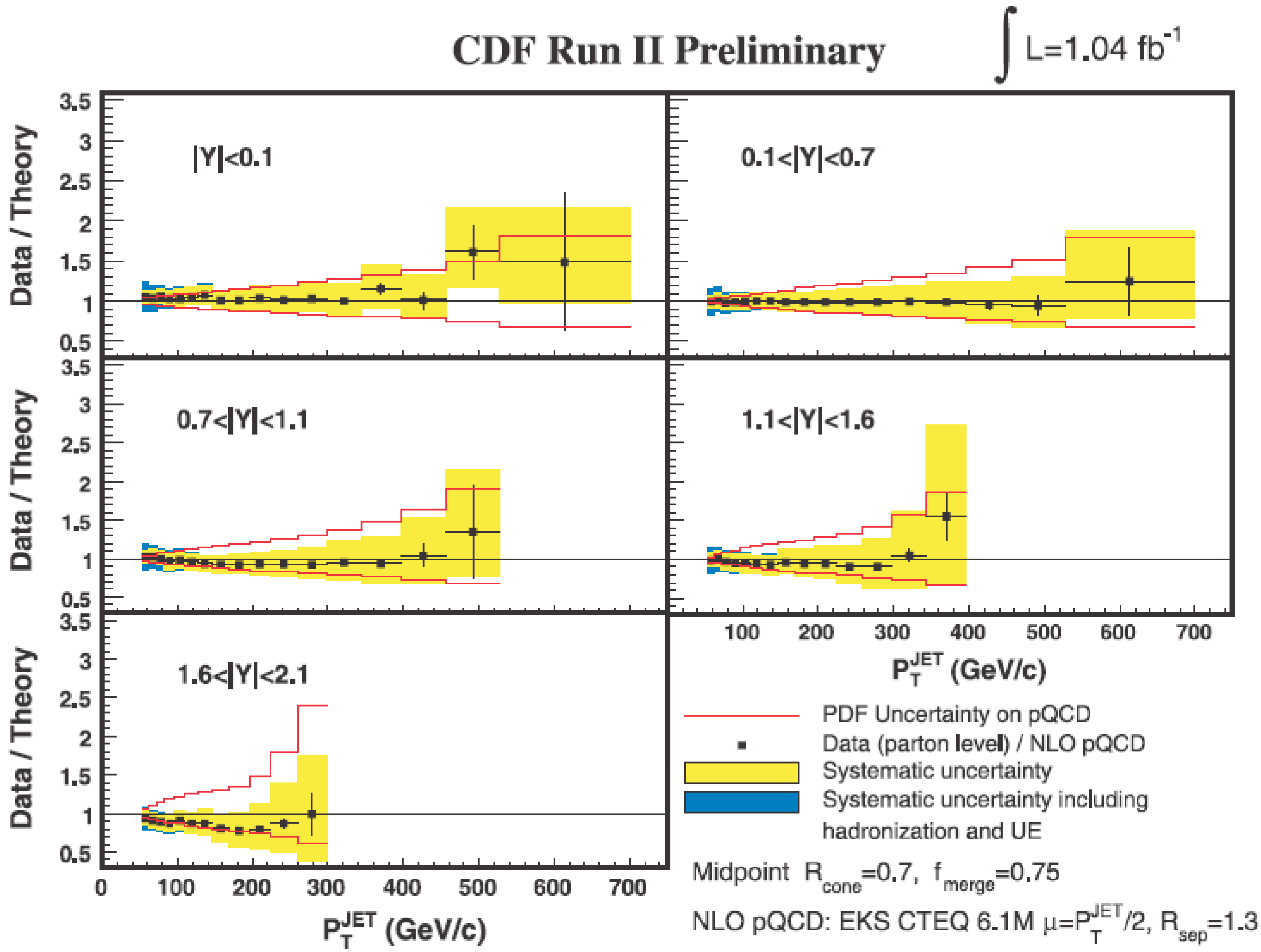


Figure 50. The inclusive jet cross section from CDF in Run 2, for several rapidity intervals using the midpoint cone algorithm, compared on a linear scale to NLO theoretical predictions using CTEQ6.1 pdfs.

Inclusive jet production at the LHC

- pdf uncertainty is sizeable at the highest transverse momenta, as at Tevatron

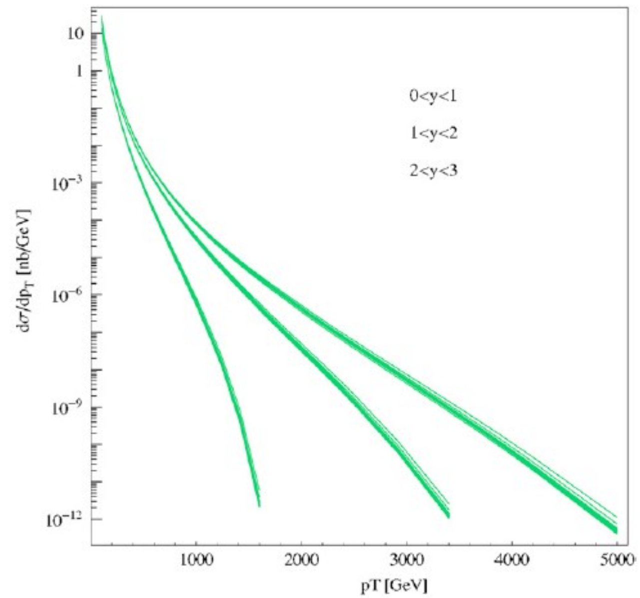


Figure 104. Inclusive jet cross section predictions for the LHC using the CTEQ6.1 central pdf and the 40 error pdfs.

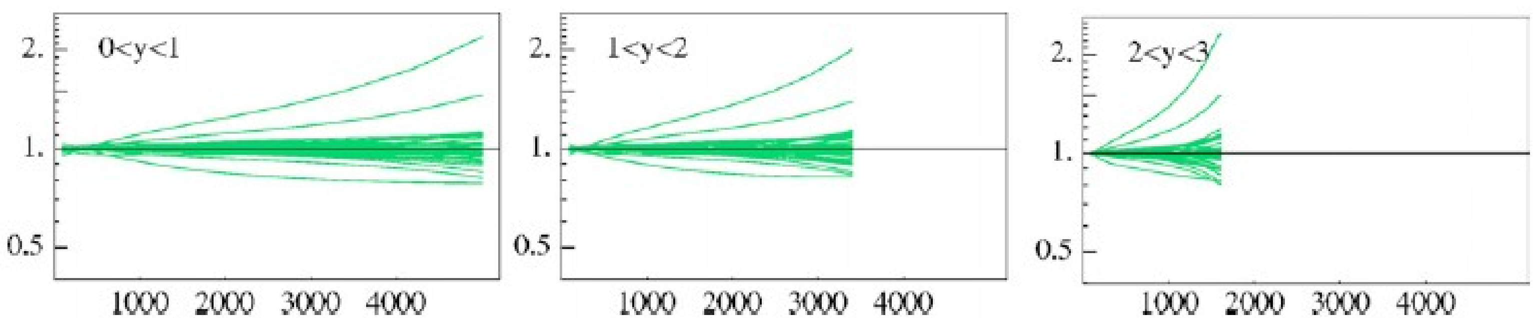


Figure 105. The ratios of the jet cross section predictions for the LHC using the CTEQ6.1 error pdfs to the prediction using the central pdf. The extremes are produced by eigenvector 15.

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•Physics isn't flying out of CTEQ at the same rate as at the Tevatron but we're preparing papers on

•update to NLO pdf's

•recent Tevatron data

•modified LO pdfs

•...and it's not too early to be thinking about Les Houches 2009

June 8-26, 2009

Bonus feature #1

gg luminosity uncertainties

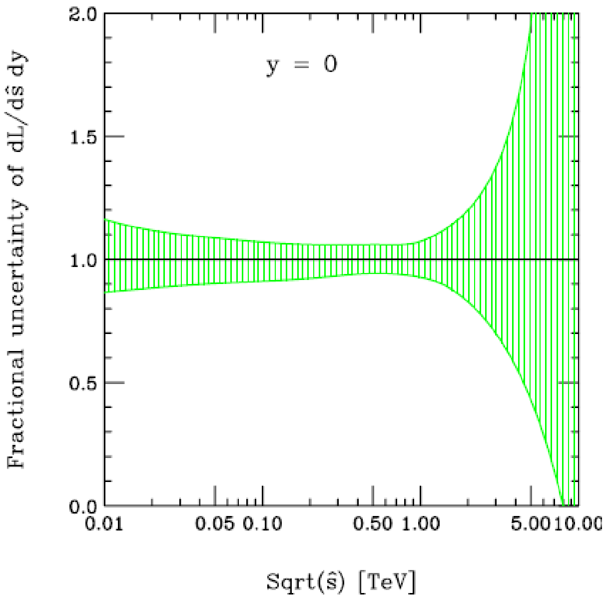
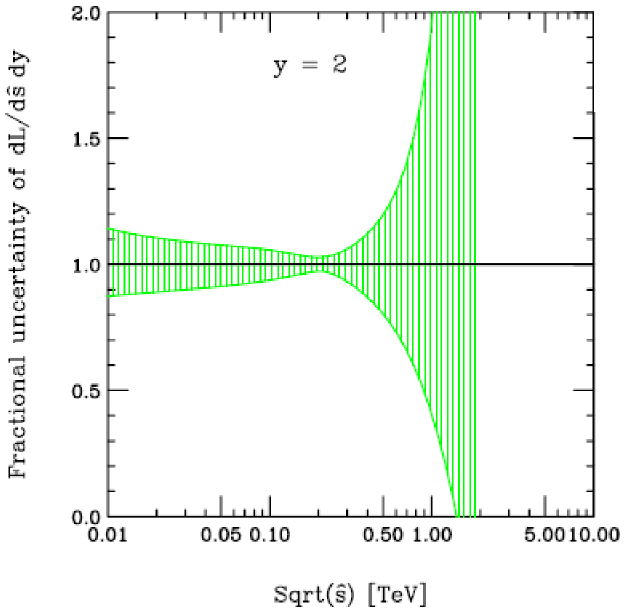
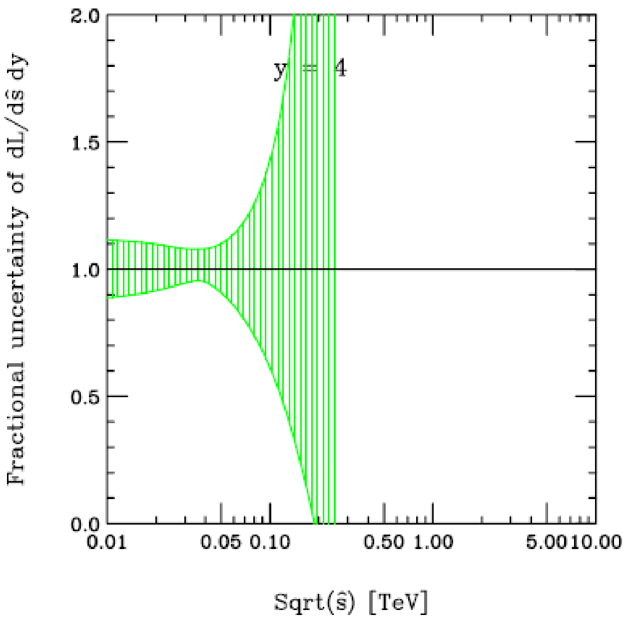


Fig. 5: Fractional uncertainty of gg luminosity at $y = 0$.





gg luminosity uncertainties

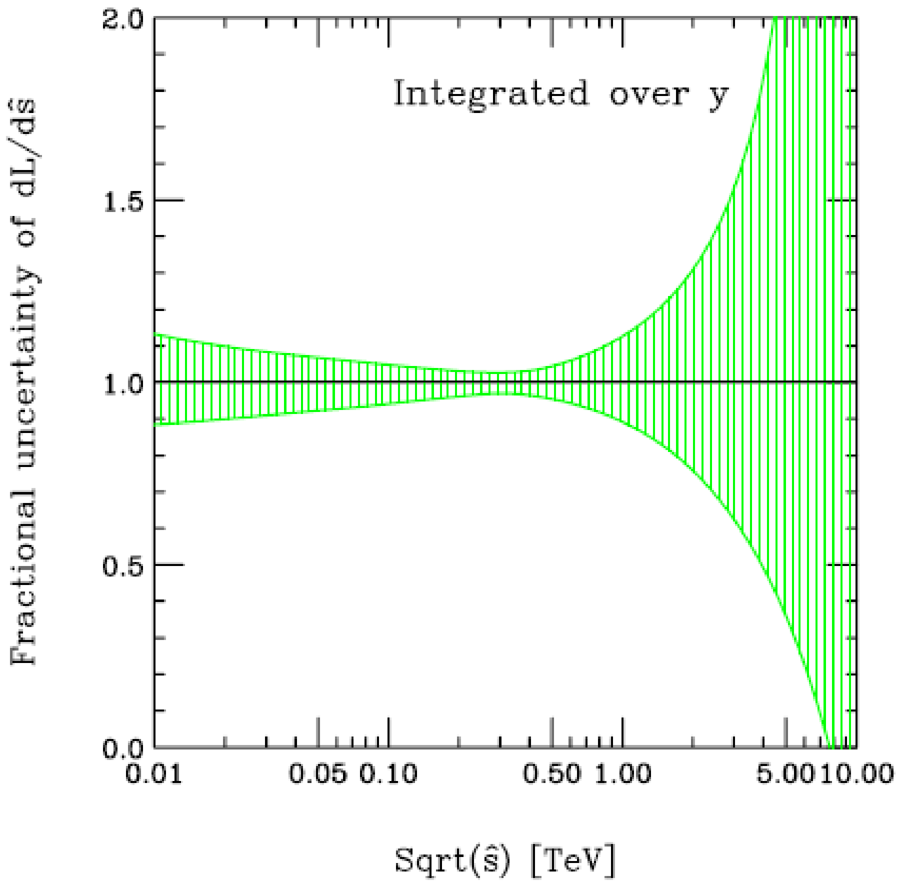


Fig. 4: Fractional uncertainty of gg luminosity integrated over y.

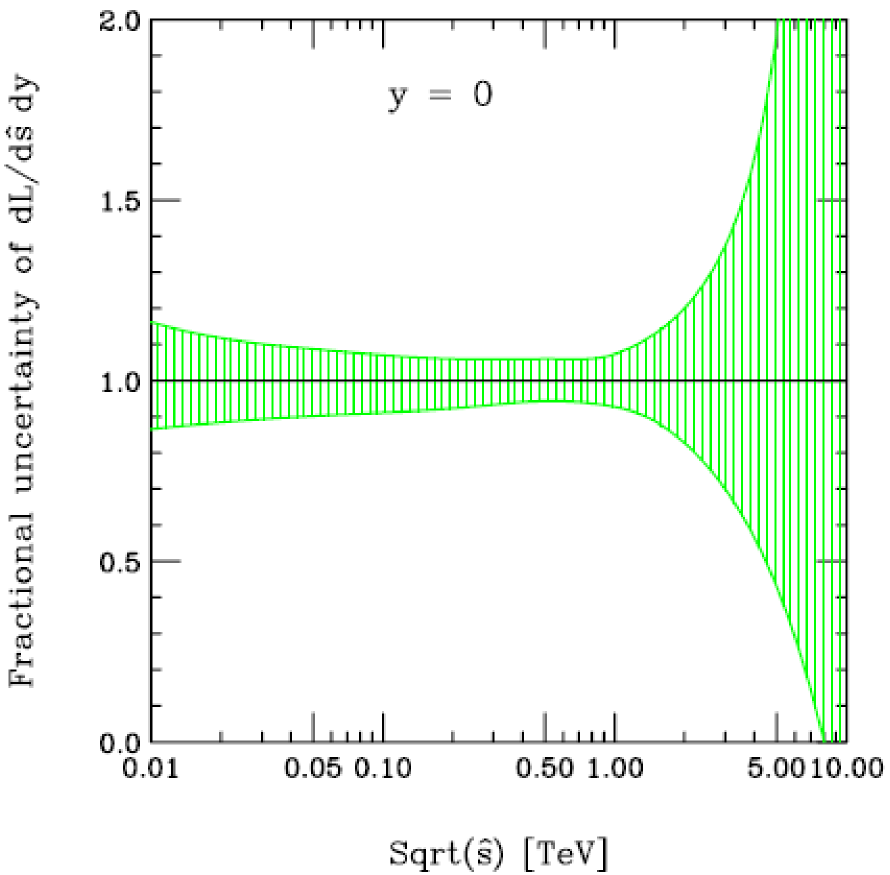


Fig. 5: Fractional uncertainty of gg luminosity at $y = 0$.

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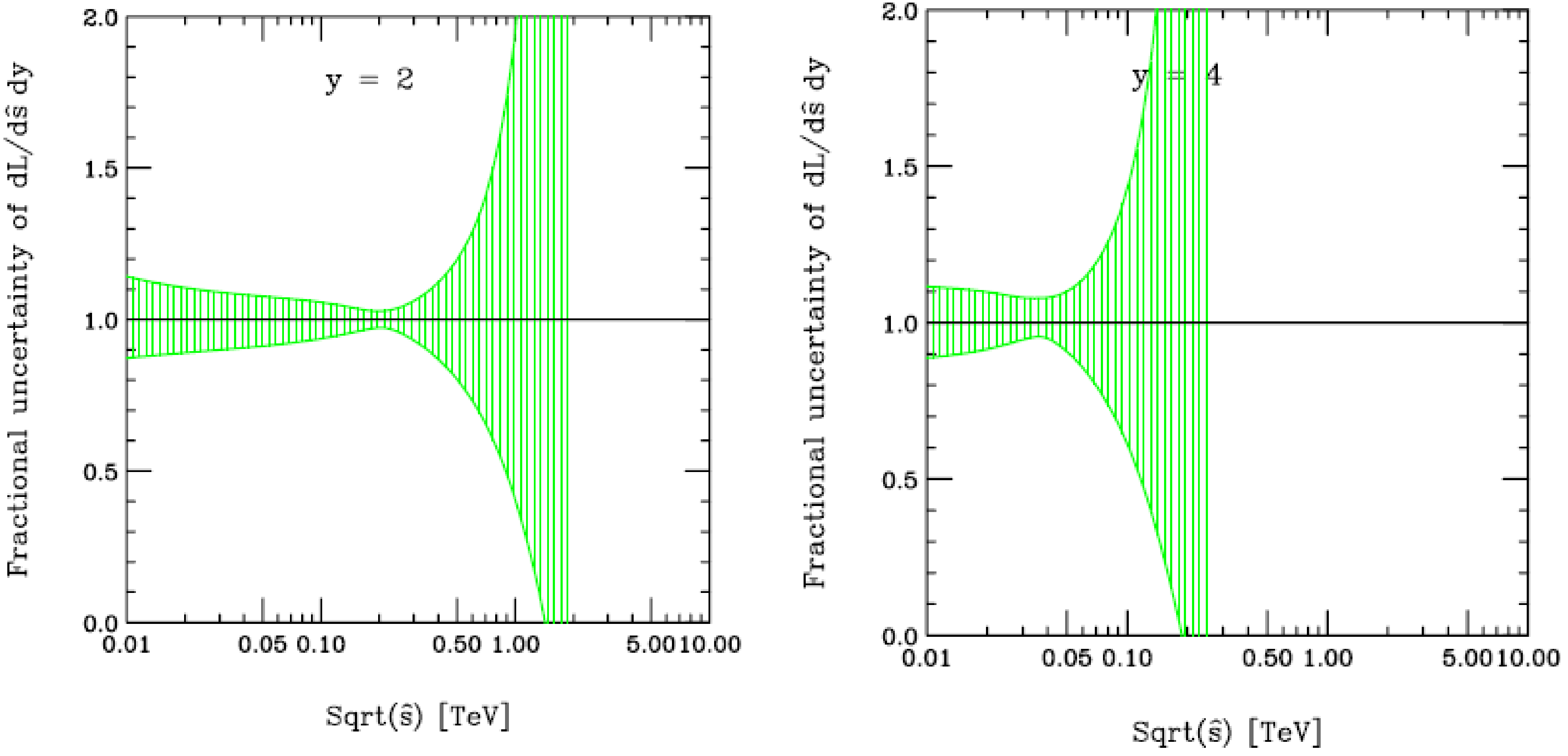
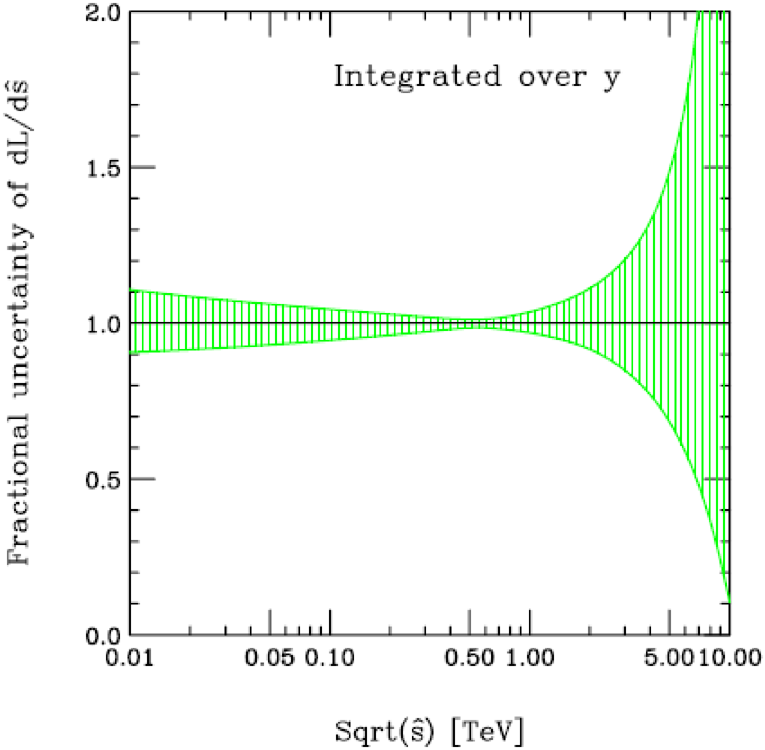
gg luminosity uncertainties



C T E Q

gq luminosity uncertainties



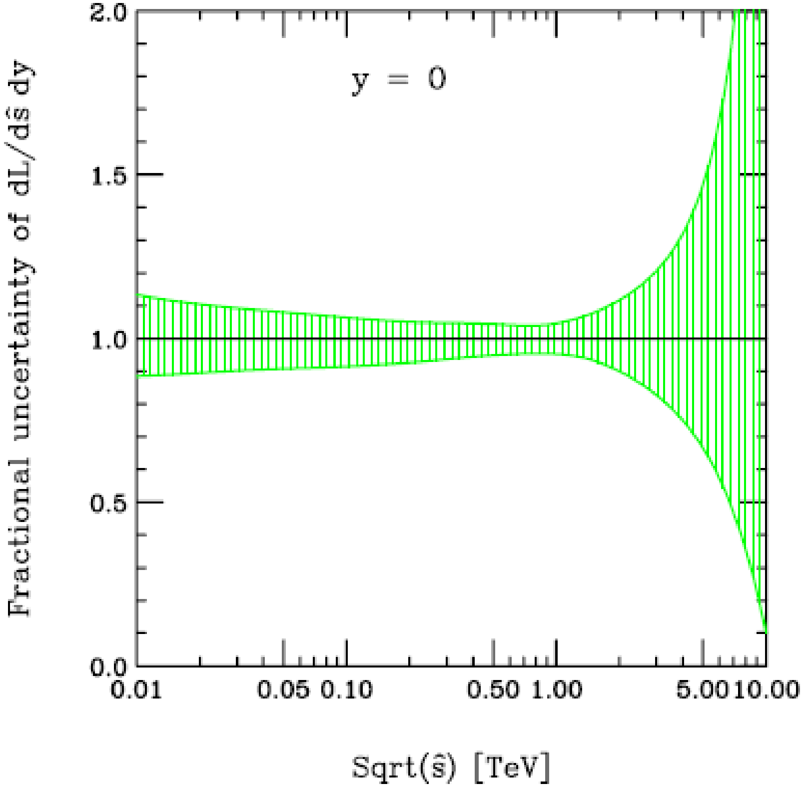
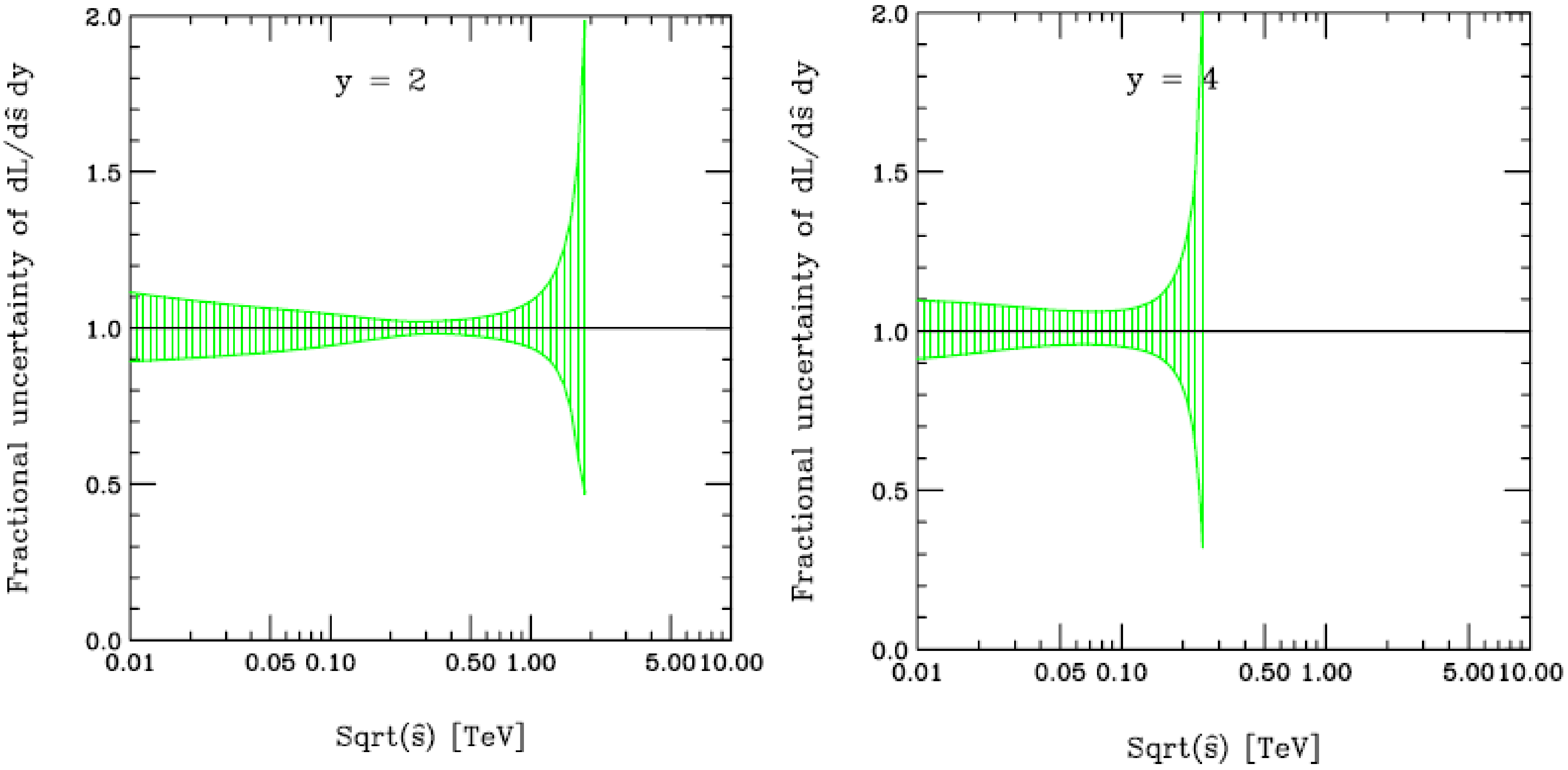


Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$,

gq luminosity uncertainties



qQ luminosity uncertainties

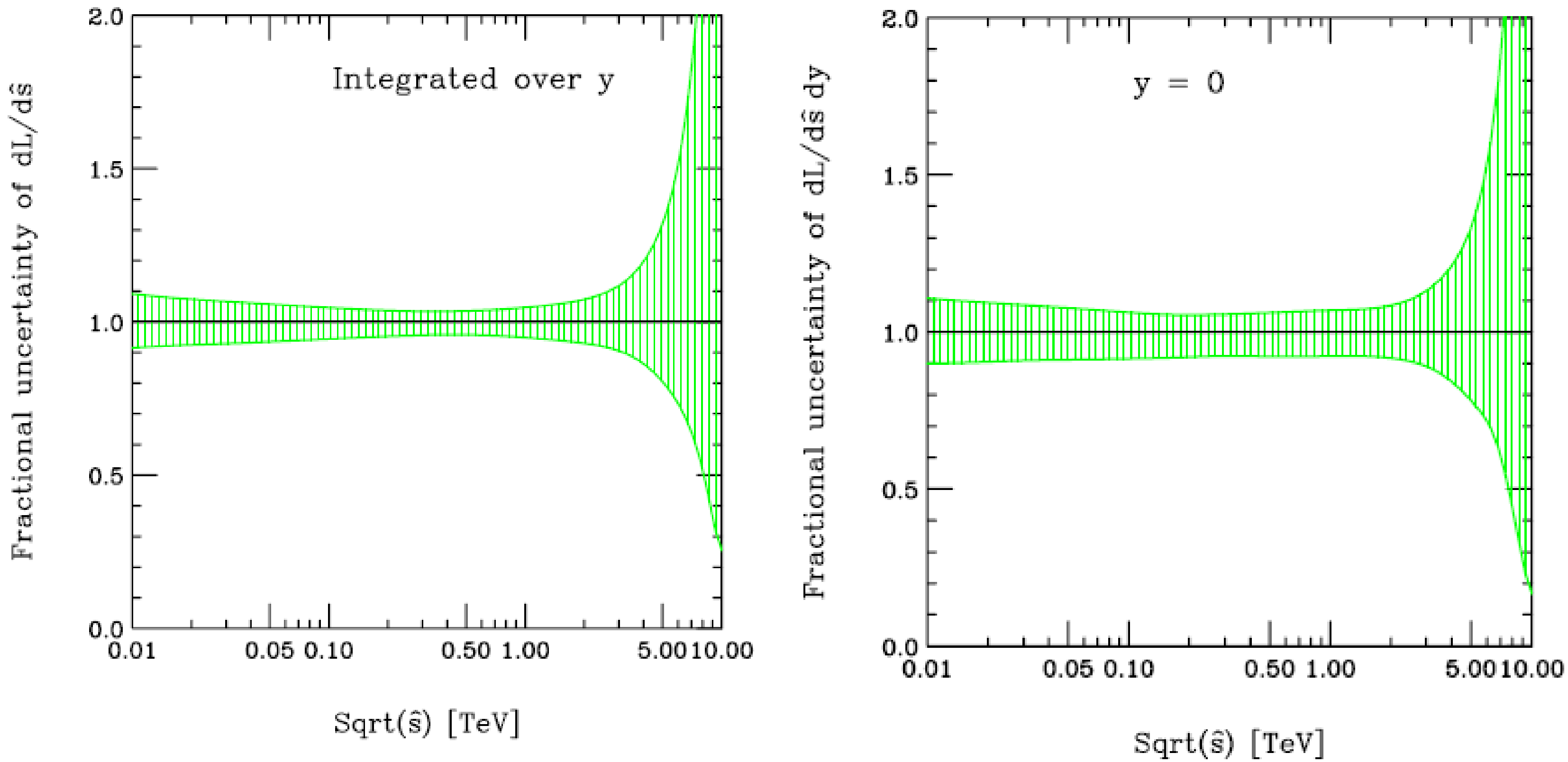


Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.

qQ luminosity uncertainties